US008911910B2

(12) **United States Patent**
Krishnan et al.

(10) **Patent No.: US 8,911,910 B2**
(45) **Date of Patent: Dec. 16, 2014**

(54) **MULTI-MODE CHARGING OF HIERARCHICAL ANODE**

(75) Inventors: **Ramkumar Krishnan**, Gilbert, AZ (US); **Cody A. Friesen**, Fort McDowell, AZ (US)

(73) Assignee: **Fluidic, Inc.**, Scottsdale, AZ (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 603 days.

(21) Appl. No.: **13/299,167**

(22) Filed: **Nov. 17, 2011**

(65) **Prior Publication Data**

US 2012/0139496 A1 Jun. 7, 2012

Related U.S. Application Data

(60) Provisional application No. 61/414,579, filed on Nov. 17, 2010.

(51) **Int. Cl.**

H01M 8/22	(2006.01)
H01M 8/18	(2006.01)
H01M 12/04	(2006.01)
H01M 8/06	(2006.01)

(52) **U.S. Cl.**
CPC ***H01M 8/184*** (2013.01); ***H01M 12/04*** (2013.01); ***H01M 8/0656*** (2013.01); *Y02E 60/528* (2013.01)
USPC **429/402**; 429/422

(58) **Field of Classification Search**
CPC . H01M 12/04; H01M 12/06; H01M 8/04082; H01M 8/04089; H01M 8/04574; H01M 8/04582; H01M 8/04895; H01M 8/04902; H01M 8/06; H01M 8/0656; H01M 8/18; H01M 8/184; Y02E 60/528; H02J 7/00; H02J 7/0008
USPC 429/402, 422
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,083,364 A	6/1937	Cook, Jr.
3,219,486 A	11/1965	Gumucio

(Continued)

FOREIGN PATENT DOCUMENTS

CN	100037	1/2012
EP	0058090	8/1982

(Continued)

OTHER PUBLICATIONS

Examiner's First Report dated Feb. 6, 2012 of Australian Innovation Patent No. 2011101611 (2 pages).

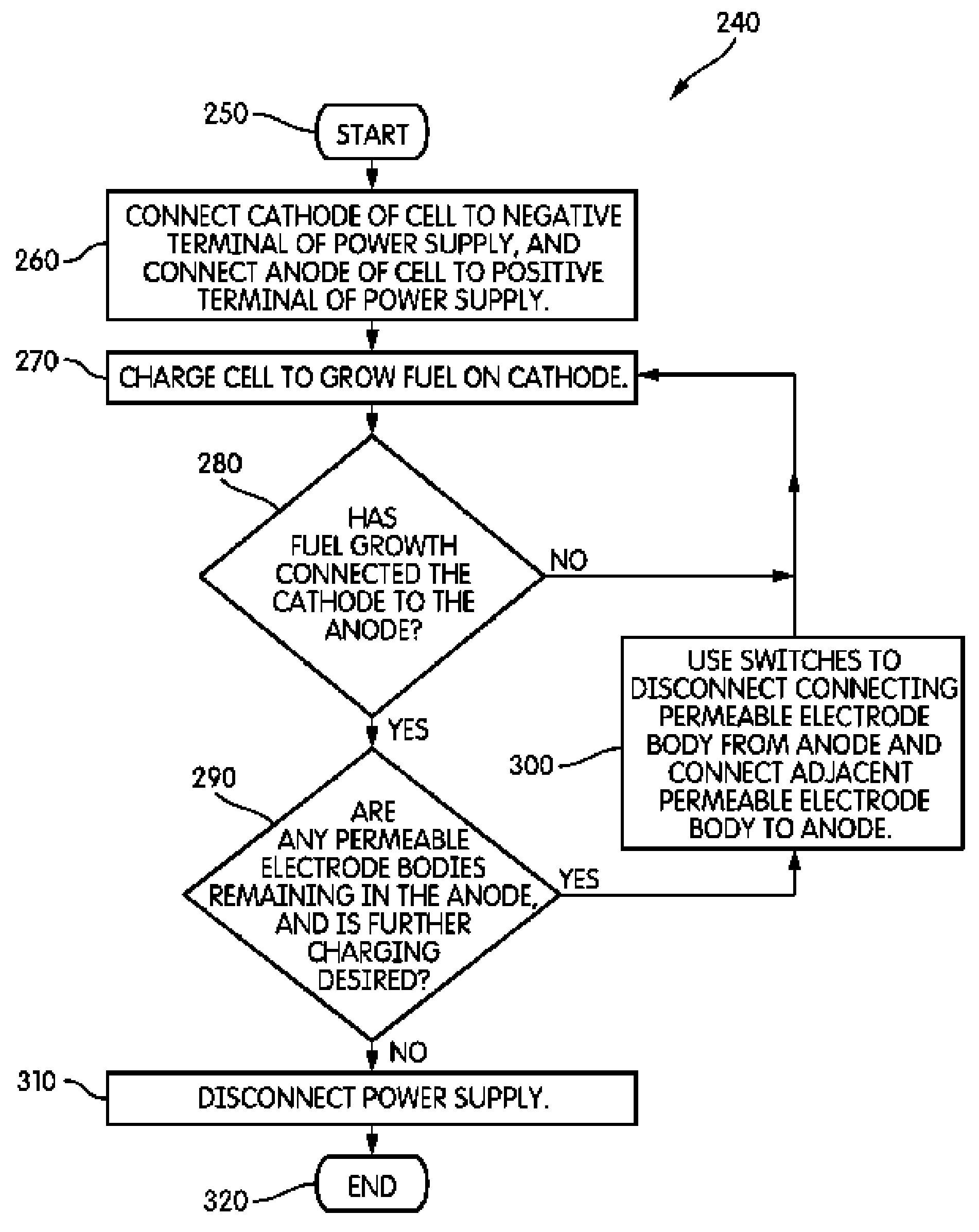
(Continued)

Primary Examiner — Raymond Alejandro
(74) *Attorney, Agent, or Firm* — Pillsbury Winthrop Shaw Pittman LLP

(57) **ABSTRACT**

One aspect of the present invention provides an electrochemical cell system comprising at least one electrochemical cell configured to be connected to a power supply to recharge the cell. The electrochemical cell system comprises a plurality of electrodes and electrode bodies therein. The electrochemical cell system further comprises a switching system configured to permit modifications of the configuration of anodes and cathodes during charging of the electrochemical cell, and a controller configured to control the switching system. The controller is configured to selectively apply the electrical current to a different number of said electrode bodies based on at least one input parameter so as to adjust a rate and density of the growth of the electrodeposited metal fuel.

33 Claims, 15 Drawing Sheets



(56) References Cited

U.S. PATENT DOCUMENTS

3,223,611	A	12/1965	Wells	
3,338,746	A	8/1967	Plust	
3,378,406	A	4/1968	Rosansky	
3,483,036	A	12/1969	Gregor	
3,525,643	A	8/1970	Spahrbier	
3,532,548	A	10/1970	Stachurski	
3,615,843	A	10/1971	Moran	
3,615,844	A	10/1971	Spengler	
3,650,837	A	3/1972	Palmer	
3,713,892	A	1/1973	Moran	
3,716,413	A	2/1973	Elsner	
3,717,505	A	2/1973	Unkle, Jr.	
3,728,244	A	4/1973	Cooley	
3,785,868	A	1/1974	Devitt	
3,801,376	A	4/1974	Lindstrom	
3,822,149	A	7/1974	Hale	
3,840,455	A	10/1974	Cooley	
3,850,696	A	11/1974	Summers	
3,886,426	A	5/1975	Daggett	
3,919,062	A	11/1975	Lundquist, Jr.	
3,972,727	A	8/1976	Cohn	
4,119,772	A	10/1978	Peters	
4,201,653	A	5/1980	ONeill et al.	
4,312,927	A	1/1982	Salmon	
4,317,863	A	3/1982	Struthers	
4,340,449	A	7/1982	Srinivasan	
4,385,101	A	5/1983	Catanzarite	
4,385,967	A	5/1983	Brady	
4,447,504	A	5/1984	Goebel	
4,461,817	A	7/1984	Itoh	
4,521,497	A	6/1985	Tamminen	
4,581,064	A	4/1986	Morrison	
4,684,585	A	8/1987	Tamminen	
4,693,946	A	9/1987	Niksa	
4,732,823	A	3/1988	Ito	
4,871,627	A	10/1989	Strong	
4,894,355	A	1/1990	Takeuchi	
5,009,755	A	4/1991	Shor	
5,104,497	A	4/1992	Tetzlaff	
5,185,218	A	2/1993	Brokman	
5,190,833	A	3/1993	Goldstein	
5,318,861	A	6/1994	Harats	
5,376,471	A	12/1994	Hunter	
5,415,949	A	5/1995	Stone	
5,431,823	A	7/1995	Gofer	
5,434,020	A	7/1995	Cooper	
5,439,758	A	8/1995	Stone	
5,458,988	A	10/1995	Putt	
5,567,540	A *	10/1996	Stone et al.	429/63
5,650,240	A	7/1997	Rogers	
5,652,068	A	7/1997	Shuster	
5,733,677	A	3/1998	Golovin	
5,850,136	A	12/1998	Kaneko	
5,935,724	A	8/1999	Spillman	
5,935,728	A	8/1999	Spillman	
5,938,899	A	8/1999	Forand	
5,972,531	A	10/1999	Kawakami	
5,998,967	A	12/1999	Umeki	
6,014,013	A	1/2000	Suppanz	
6,025,696	A	2/2000	Lenhart	
6,027,834	A	2/2000	Hayashi	
6,034,506	A	3/2000	Hall	
6,046,514	A	4/2000	Rouillard	
6,054,840	A	4/2000	Nakanishi	
6,057,052	A	5/2000	Shrim	
6,091,230	A	7/2000	Winzer	
6,121,752	A	9/2000	Kitahara	
6,127,061	A	10/2000	Shun	
6,153,328	A	11/2000	Colborn	
6,162,555	A	12/2000	Gutierrez	
6,165,638	A	12/2000	Spillman	
6,207,037	B1	3/2001	Dartnell	
6,211,650	B1	4/2001	Mumaw	
6,265,846	B1	7/2001	Flechsig	
6,271,646	B1	8/2001	Evers	
6,277,508	B1	8/2001	Reiser	
6,312,846	B1	11/2001	Marsh	
6,355,369	B1	3/2002	Iarochenko	
6,379,828	B1	4/2002	Worth	
6,383,673	B1	5/2002	Faris	
6,383,675	B1	5/2002	Zhong	
6,410,174	B1	6/2002	Faris	
6,458,480	B1	10/2002	Morris	
6,465,638	B2	10/2002	Gorman	
6,472,093	B2	10/2002	Faris	
6,541,941	B2	4/2003	Adams	
6,544,678	B2	4/2003	Faris	
6,558,830	B2	5/2003	Faris	
6,562,494	B1	5/2003	Tsai	
6,562,504	B2	5/2003	Faris	
6,566,000	B1	5/2003	Iarochenko	
6,569,555	B1	5/2003	Faris	
6,579,637	B1	6/2003	Savage	
6,586,909	B1	7/2003	Trepka	
6,641,943	B1 *	11/2003	Faris et al.	429/402
6,646,418	B1	11/2003	Xie	
6,649,294	B2	11/2003	Faris	
6,653,252	B2	11/2003	Kawahara	
6,673,490	B2	1/2004	Miki	
6,677,077	B2	1/2004	Spillman	
6,706,433	B2	3/2004	Pinto et al.	
6,713,206	B2	3/2004	Markoski	
6,756,149	B2	6/2004	Knights	
6,762,587	B1	7/2004	Barbetta	
6,764,588	B2	7/2004	Smedley	
6,787,260	B2	9/2004	Smedley	
6,802,946	B2	10/2004	Basol	
6,811,903	B2	11/2004	Vartak	
6,822,423	B2	11/2004	Yau	
6,838,203	B2	1/2005	Zheng	
6,855,455	B1	2/2005	Berger	
6,858,347	B2	2/2005	Tanigawa	
6,866,950	B2	3/2005	Connor	
6,902,602	B2	6/2005	Keefer	
6,911,274	B1	6/2005	Colborn	
6,942,105	B2	9/2005	Smedley	
6,967,064	B2	11/2005	Haltiner, Jr.	
6,986,964	B2	1/2006	Faris	
7,020,355	B2	3/2006	Lahann	
7,126,310	B1	10/2006	Barron	
7,150,933	B1	12/2006	McLean	
7,201,857	B2	4/2007	Ovshinsky	
7,226,676	B2	6/2007	Faris	
7,238,440	B2	7/2007	Damore	
7,252,898	B2	8/2007	Markoski	
7,270,906	B2	9/2007	Haltiner, Jr.	
7,273,541	B2	9/2007	Choban	
7,276,309	B2	10/2007	Smedley	
7,279,245	B1	10/2007	Clark	
7,291,186	B2	11/2007	Zhang	
7,303,835	B2	12/2007	Mathias	
7,466,104	B2	12/2008	Wang	
7,468,221	B2	12/2008	Lafollette	
7,482,081	B2	1/2009	Hong	
7,488,547	B1	2/2009	Iacovelli	
7,535,199	B2	5/2009	Kimura	
7,598,706	B2	10/2009	Koski	
7,670,575	B2	3/2010	Jarvinen	
7,670,705	B2	3/2010	Ueda	
7,670,724	B1	3/2010	Chan	
7,722,988	B2	5/2010	Webber	
8,058,165	B2	11/2011	Kawano	
2001/0007725	A1	7/2001	Faris	
2002/0015871	A1	2/2002	Tao	
2002/0028372	A1	3/2002	Ohlsen	
2002/0045075	A1	4/2002	Pinto	
2002/0076602	A1	6/2002	Finkelshtain	
2002/0098398	A1	7/2002	Chen	
2002/0142203	A1	10/2002	Ma	
2002/0146600	A1	10/2002	Vartak	
2003/0054217	A1	3/2003	Faris	
2003/0077501	A1	4/2003	Knights	
2003/0099882	A1	5/2003	Hampden-Smith	
2003/0134163	A1	7/2003	Markoski	

(56) References Cited

U.S. PATENT DOCUMENTS

2003/0143446	A1	7/2003	Faris	
2003/0165727	A1	9/2003	Priestnall	
2003/0190504	A1	10/2003	Fisher	
2003/0198862	A1	10/2003	Struthers	
2004/0005488	A1	1/2004	Faris	
2004/0023112	A1	2/2004	Lin	
2004/0053132	A1	3/2004	Smedley	
2004/0058203	A1	3/2004	Priestnall	
2004/0058217	A1	3/2004	Ohlsen	
2004/0058226	A1	3/2004	Lamarre	
2004/0121208	A1	6/2004	James	
2004/0146764	A1	7/2004	Tsai	
2004/0157092	A1	8/2004	Kimberg	
2004/0157101	A1	8/2004	Smedley	
2004/0175603	A1	9/2004	Yang	
2004/0180246	A1	9/2004	Smedley	
2004/0185323	A1	9/2004	Fowler	
2004/0185328	A1	9/2004	Lin	
2004/0225249	A1	11/2004	Leonard	
2004/0229107	A1	11/2004	Smedley	
2004/0247969	A1	12/2004	Faris	
2004/0265684	A1	12/2004	Faris	
2005/0019634	A1	1/2005	Legg	
2005/0019651	A1	1/2005	Tsai	
2005/0031911	A1	2/2005	Venkatesan	
2005/0084737	A1	4/2005	Wine	
2005/0123815	A1	6/2005	Tsai	
2005/0170245	A1	8/2005	Vartak	
2005/0196656	A1	9/2005	Gomez	
2005/0208343	A1	9/2005	Kim	
2005/0233191	A1	10/2005	Ushio	
2006/0003217	A1	1/2006	Cohen	
2006/0024551	A1	2/2006	Smotkin	
2006/0038536	A1	2/2006	Lafollette	
2006/0076295	A1	4/2006	Leonard	
2006/0127731	A1	6/2006	Faris	
2006/0210867	A1	9/2006	Kenis	
2006/0228622	A1	10/2006	Cohen	
2006/0234855	A1	10/2006	Gorte	
2006/0269826	A1	11/2006	Katz	
2006/0292407	A1	12/2006	Gervasio	
2007/0020496	A1	1/2007	Pelton	
2007/0031714	A1 *	2/2007	Huang	429/27
2007/0048577	A1	3/2007	Ringeisen	
2007/0077491	A1	4/2007	Burchardt	
2007/0092787	A1	4/2007	WangChen	
2007/0120091	A1	5/2007	Ovshinsky	
2007/0141415	A1	6/2007	Yang	
2007/0141430	A1	6/2007	Huang	
2007/0141432	A1	6/2007	Wang	
2007/0141440	A1	6/2007	Yang	
2007/0141450	A1	6/2007	Yang	
2007/0154766	A1	7/2007	Baik	
2007/0166602	A1	7/2007	Burchardt	
2007/0184314	A1	8/2007	Kagami	
2007/0224500	A1	9/2007	White	
2007/0234900	A1	10/2007	Soloveichik	
2007/0237993	A1	10/2007	Carlsson	
2007/0248845	A1	10/2007	Armstrong	
2007/0248868	A1	10/2007	Haltiner	
2007/0259234	A1	11/2007	Chua	
2007/0264550	A1	11/2007	Zhang	
2007/0269695	A1	11/2007	Yamazaki	
2007/0278107	A1	12/2007	Barnett	
2007/0287034	A1	12/2007	Minteer	
2008/0008911	A1	1/2008	Stroock	
2008/0009780	A1	1/2008	Leonard	
2008/0026265	A1	1/2008	Markoski	
2008/0032170	A1	2/2008	Wainright	
2008/0044721	A1	2/2008	Heller	
2008/0145719	A1	6/2008	Yang	
2008/0145721	A1	6/2008	Shapiro	
2008/0145737	A1	6/2008	Cai	
2008/0154101	A1	6/2008	Jain	
2008/0231231	A1	9/2008	Hartzog	
2008/0241617	A1	10/2008	Sato	
2008/0252257	A1	10/2008	Sufrin-Disler	
2008/0268341	A1	10/2008	Zhang	
2009/0027006	A1	1/2009	Vezzini	
2009/0081488	A1	3/2009	Sato	
2009/0117429	A1	5/2009	Zillmer	
2009/0123796	A1 *	5/2009	Takahashi et al.	429/17
2009/0167242	A1	7/2009	Naganuma	
2009/0230921	A1	9/2009	Hsu	
2009/0284229	A1	11/2009	Friesen	
2009/0286149	A1	11/2009	Ci	
2009/0305090	A1	12/2009	Chuang	
2010/0062303	A1	3/2010	Bae	
2010/0119883	A1	5/2010	Friesen	
2010/0285375	A1	11/2010	Friesen	
2010/0316935	A1	12/2010	Friesen	
2011/0039181	A1	2/2011	Friesen	
2011/0044528	A1	2/2011	Tsuchiya	
2011/0070506	A1	3/2011	Friesen	
2011/0086278	A1	4/2011	Friesen	
2011/0189551	A1	8/2011	Friesen	
2011/0200893	A1	8/2011	Friesen	
2011/0250512	A1	10/2011	Friesen	
2011/0305959	A1	12/2011	Friesen	
2011/0316485	A1	12/2011	Krishnan	
2012/0015264	A1	1/2012	Friesen	
2012/0068667	A1	3/2012	Friesen	

FOREIGN PATENT DOCUMENTS

EP	0277937	A1	8/1988
EP	0589144		9/1996
EP	0589144	B1	9/1996
GB	1286173	A1	8/1972
WO	WO8905528		6/1989
WO	2008058165		5/2008
WO	2010065890	A1	6/2010
WO	2011035176		3/2011
WO	2011/044528		4/2011
WO	2011044528		4/2011
WO	2011163553	A1	12/2011
WO	2011012364	A1	1/2012

OTHER PUBLICATIONS

Cherepy et al., “A Zinc/Air Fuel Cell for Electric Vehicles,” IEEE publication, 1999, pp. 11-13.

Cohen et al., “Fabrication and preliminary testing of a planar membraneless microchannel fuel cell,” J. Power Sources, 2005,139, 96-105.

Ferrigno et al., “Membraneless Vanadium Redox Fuel Cell Using Laminar Flow,” J. Am. Chem. Soc. 2002, 124, pp. 12930-12931.

Jayashree et al., “Air-Breathing Laminar Flow-Based Microfluidic Fuel Cell,” J. Am. Chem. Soc., 2005, 127, pp. 16758-16759.

Salloum et al., “Sequential flow membraneless microfluidic fuel cell with porous electrodes,” Journal of Power Sources 180, 2008, pp. 243-252.

Smedley et al., “A regenerative zinc-air fuel cell,” Journal of Power Sources, vol. 165, 2007, pp. 897-904.

Jorne et al. “Journal of the Electrochemical Society,” vol. 134 No. 6, pp. 1399-1402 (Jun. 1987).

Thirsk (Electrochemistry vol. 4 p. 16, Thirsk, ed. The Chemical Society Great Britain Oxford Alden Press 1974).

Final Office Action dated Aug. 29, 2013 of U.S. Appl. No. 12/885,268, filed Sep. 17, 2010 (15 pages).

“Application Note: FSA337 Single Pole/Triple Throw Eliminates Second Single Pole/Double Throw and Reduces Board Space”. (c)2002 Fairchild Semiconductor Corporation (Dec. 2002).

* cited by examiner

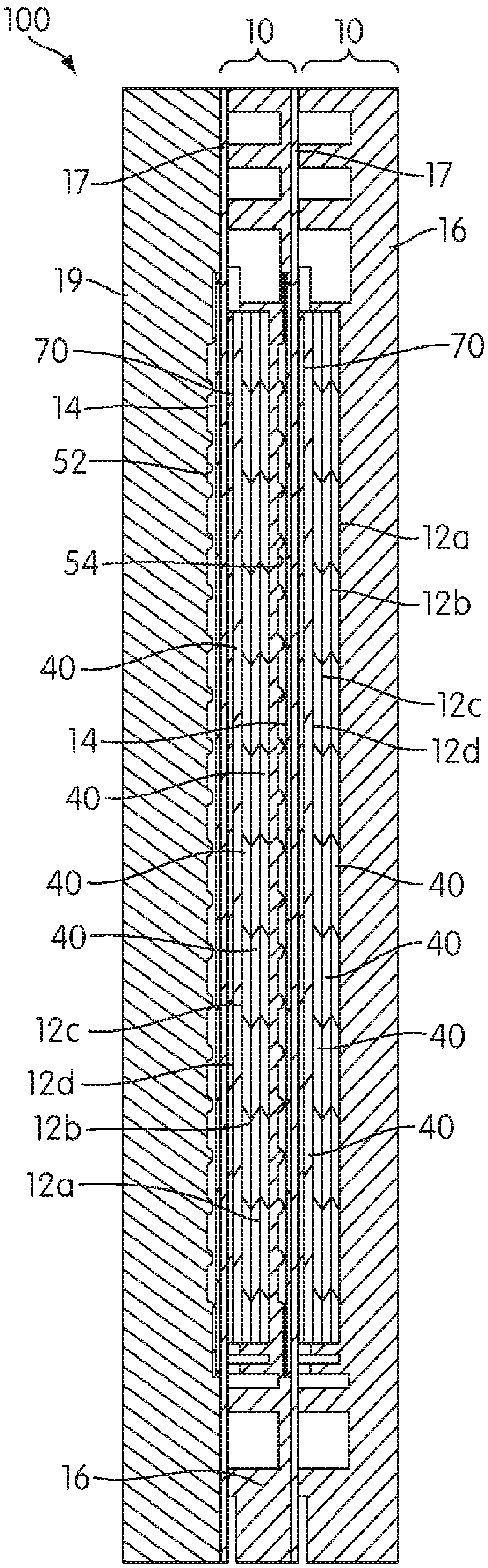

100
10
10
17
17
16
19
70
70
14
52
12a
54
12b
40
12c
14
12d
40
40
40
40
40
12c
40
12d
12b
40
12a
16

FIG. 1

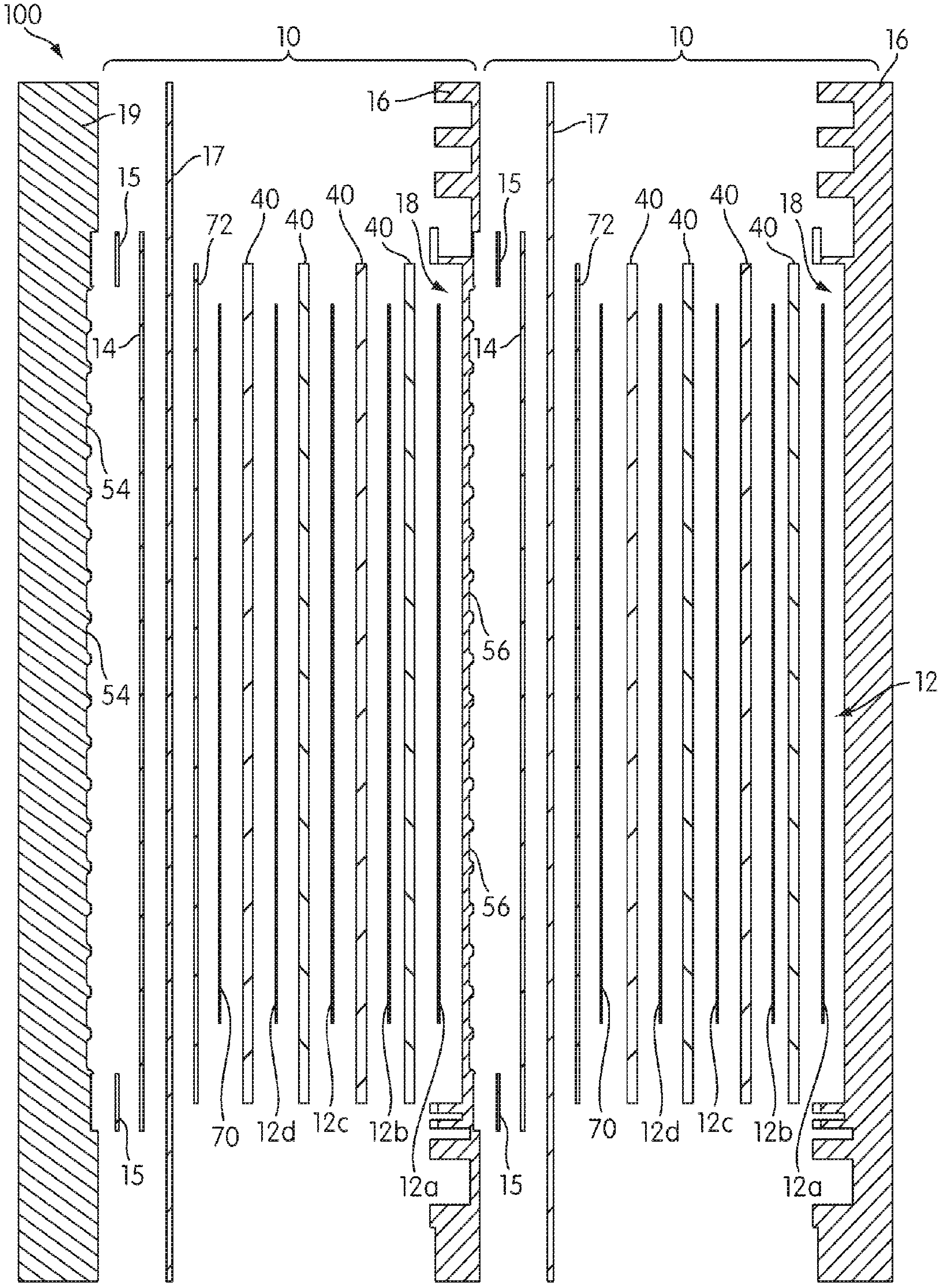

100
10
10
16
19
16
17
17
15
15
40
40
72
40
40
40
18
72
40
40
40
40
18
14
14
54
54
56
56
12
70
12d
12c
12b
12a
70
12d
12c
12b
12a
15
15

FIG. 2

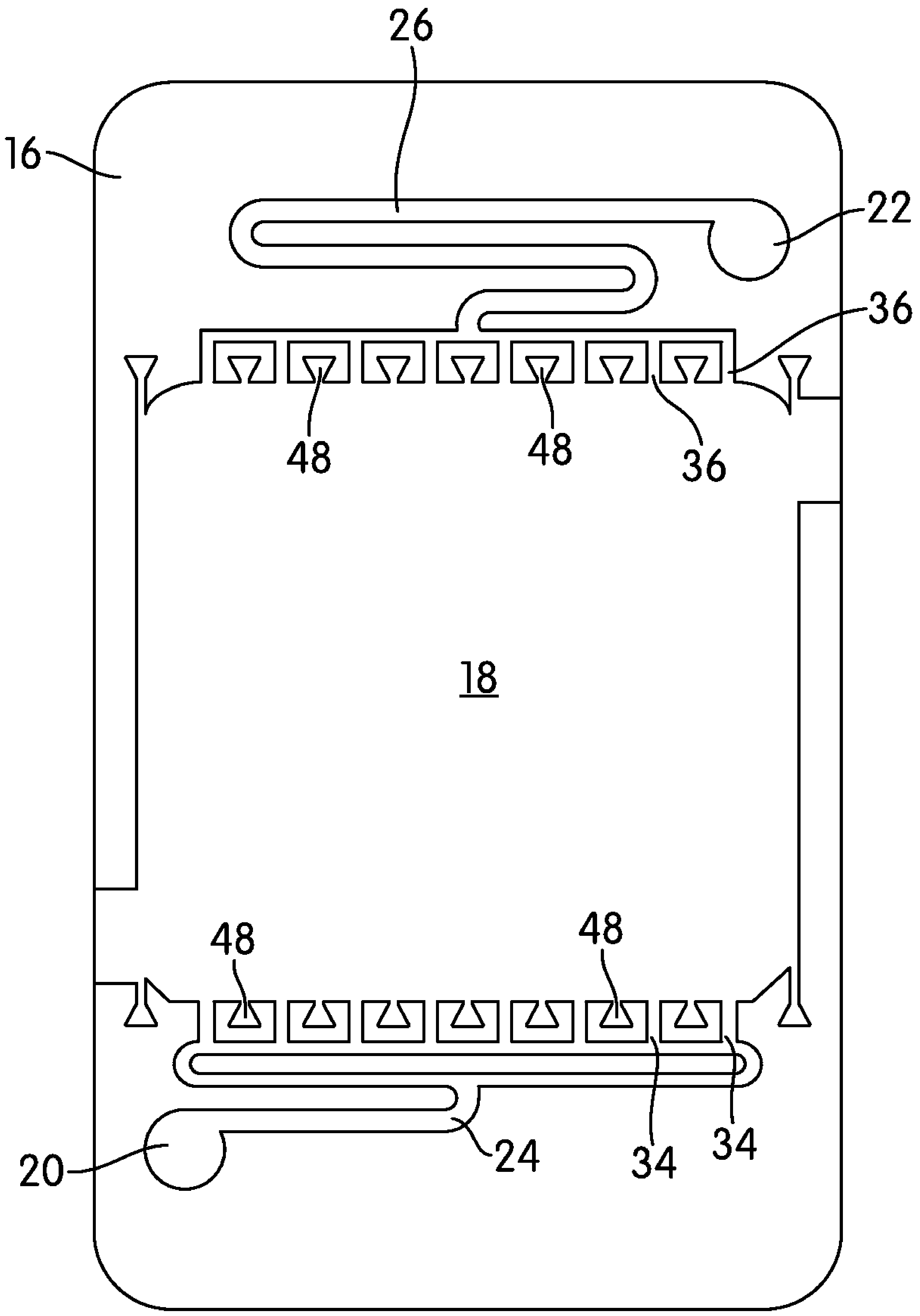


FIG. 3

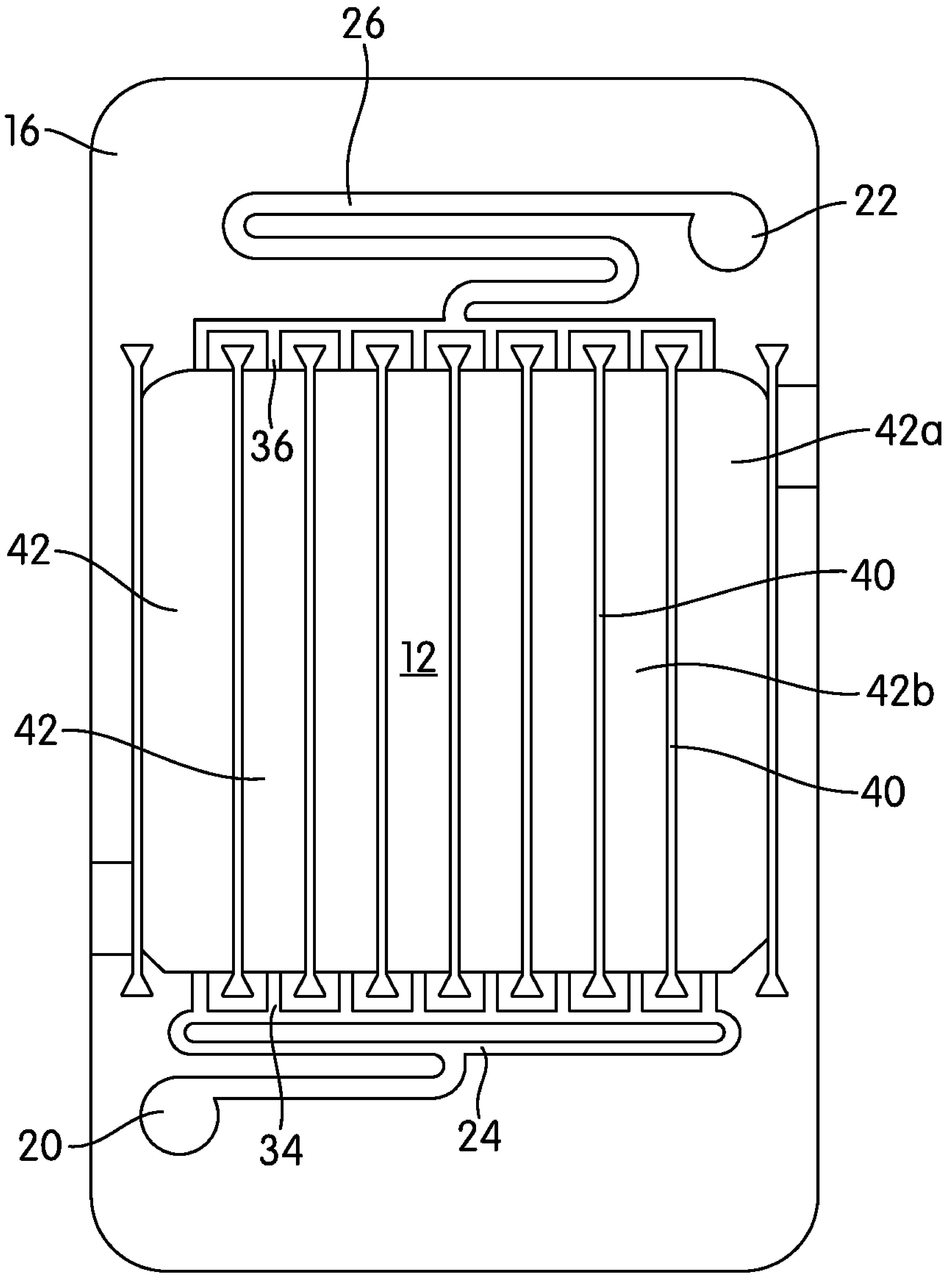


FIG. 4

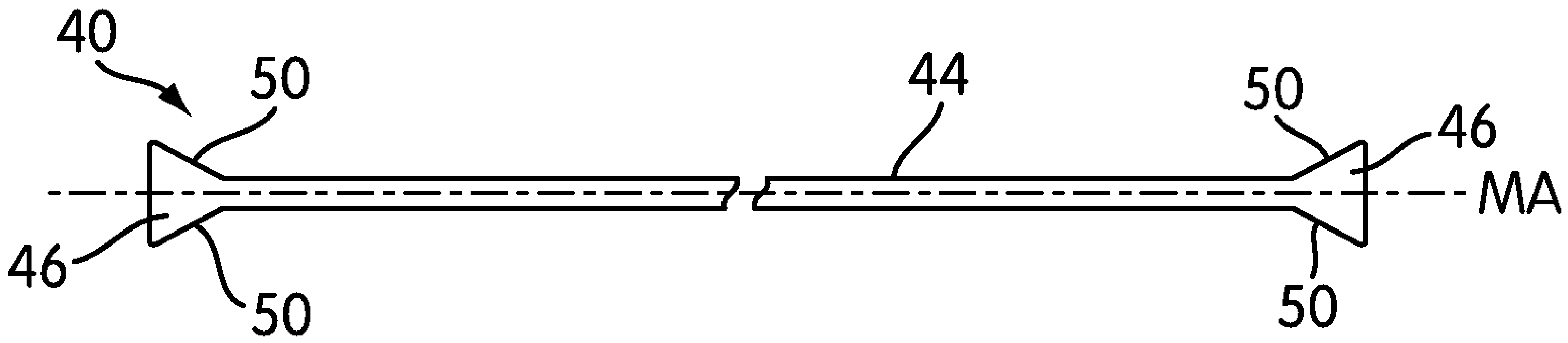


FIG. 5

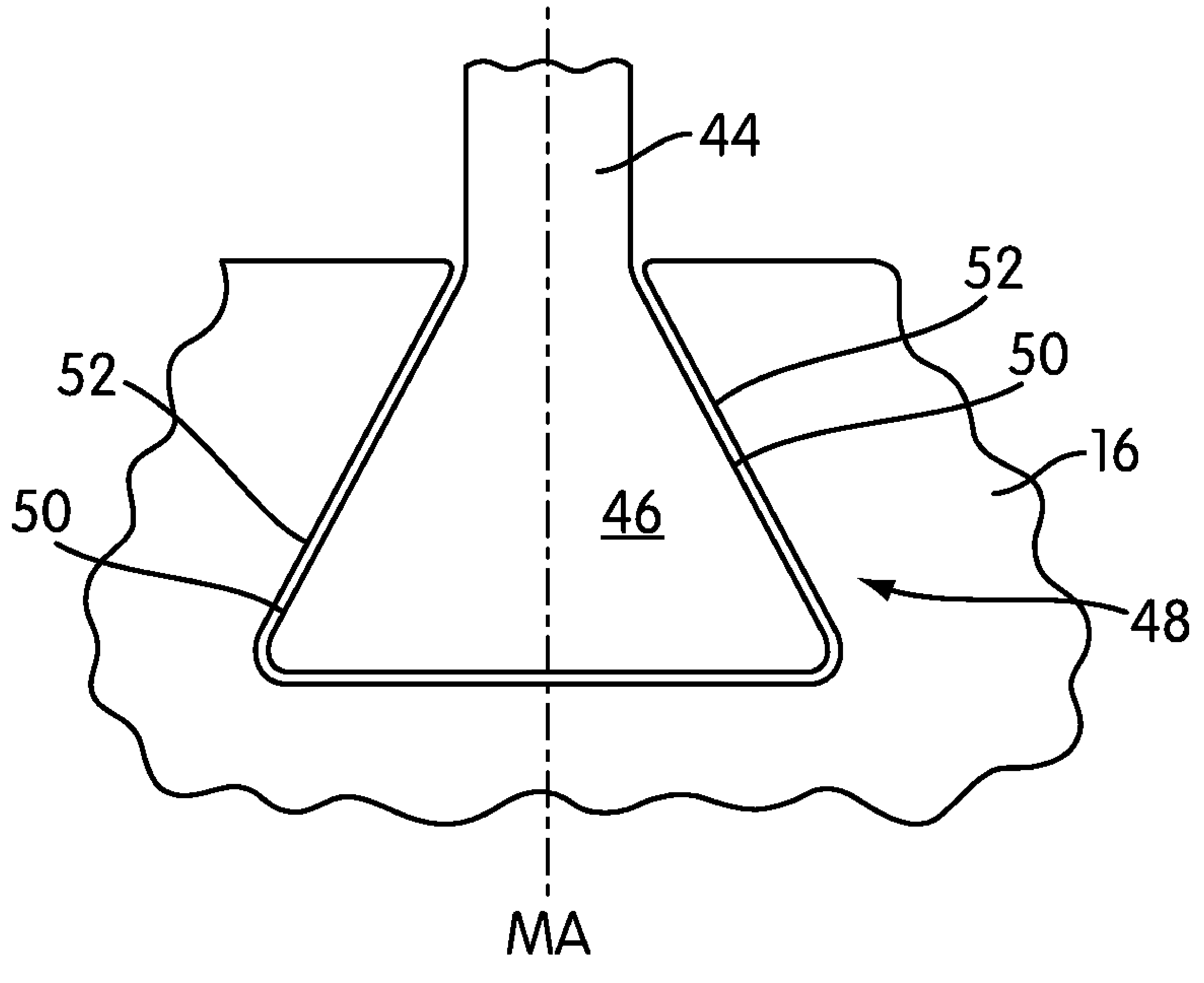


FIG. 6

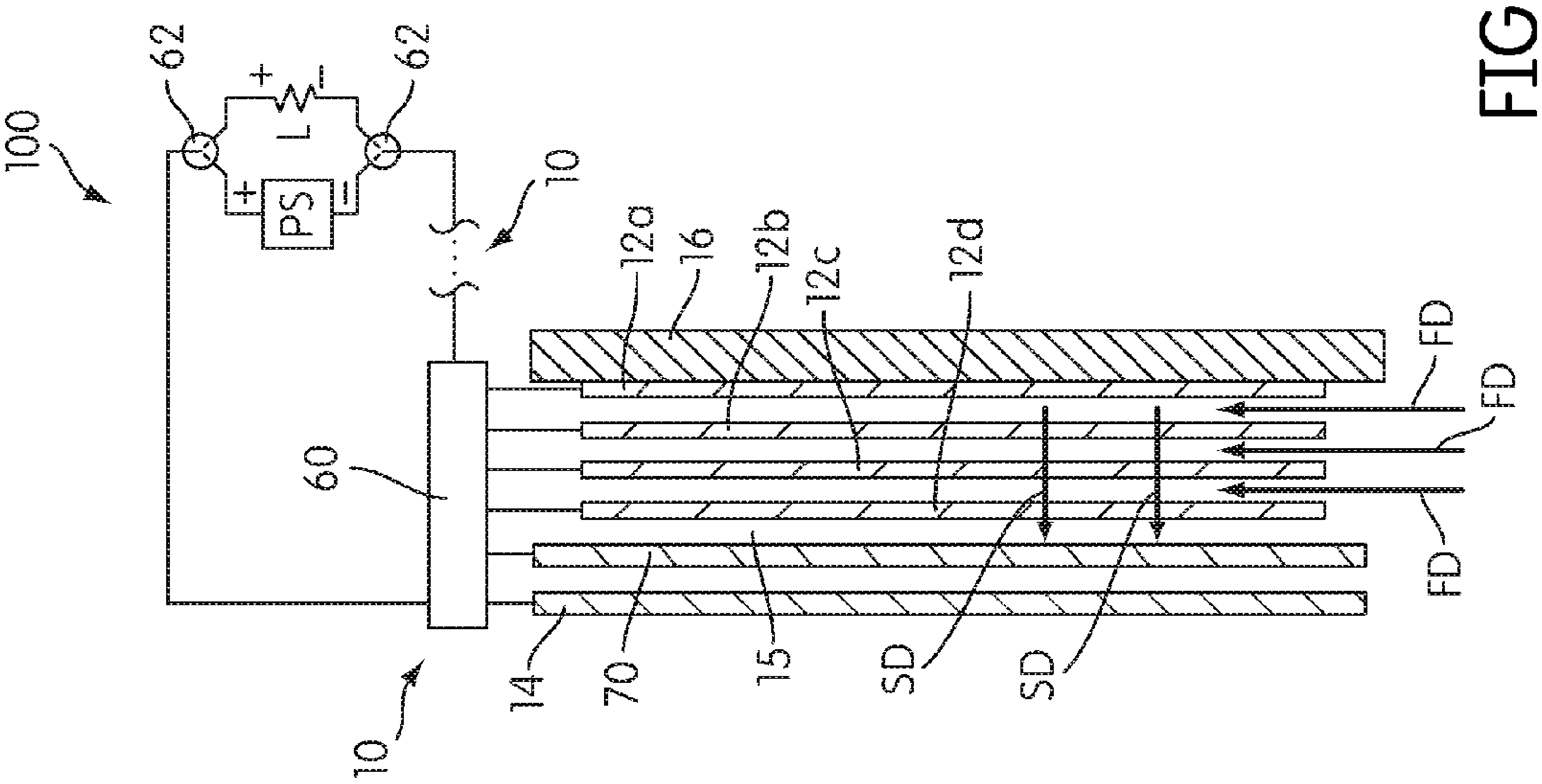

100
62
+
-
L
62
+
PS
-
10
60
12a
16
12b
12c
12d
FD
FD
FD
FD
10
14
70
15
SD
SD

FIG. 8

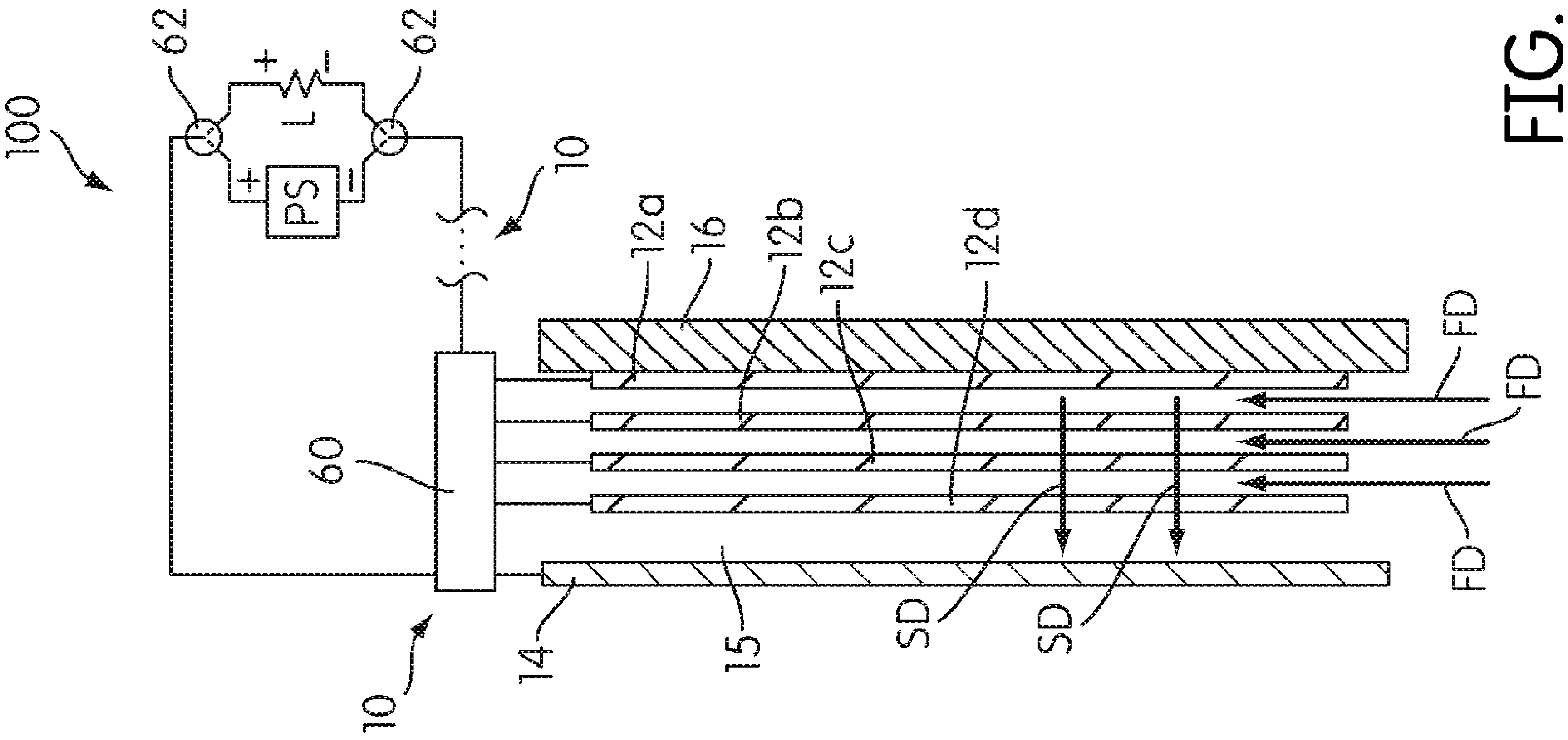

100
62
+
-
L
62
+
PS
-
10
60
12a
16
12b
12c
12d
FD
FD
FD
10
14
15
SD
SD

FIG. 7

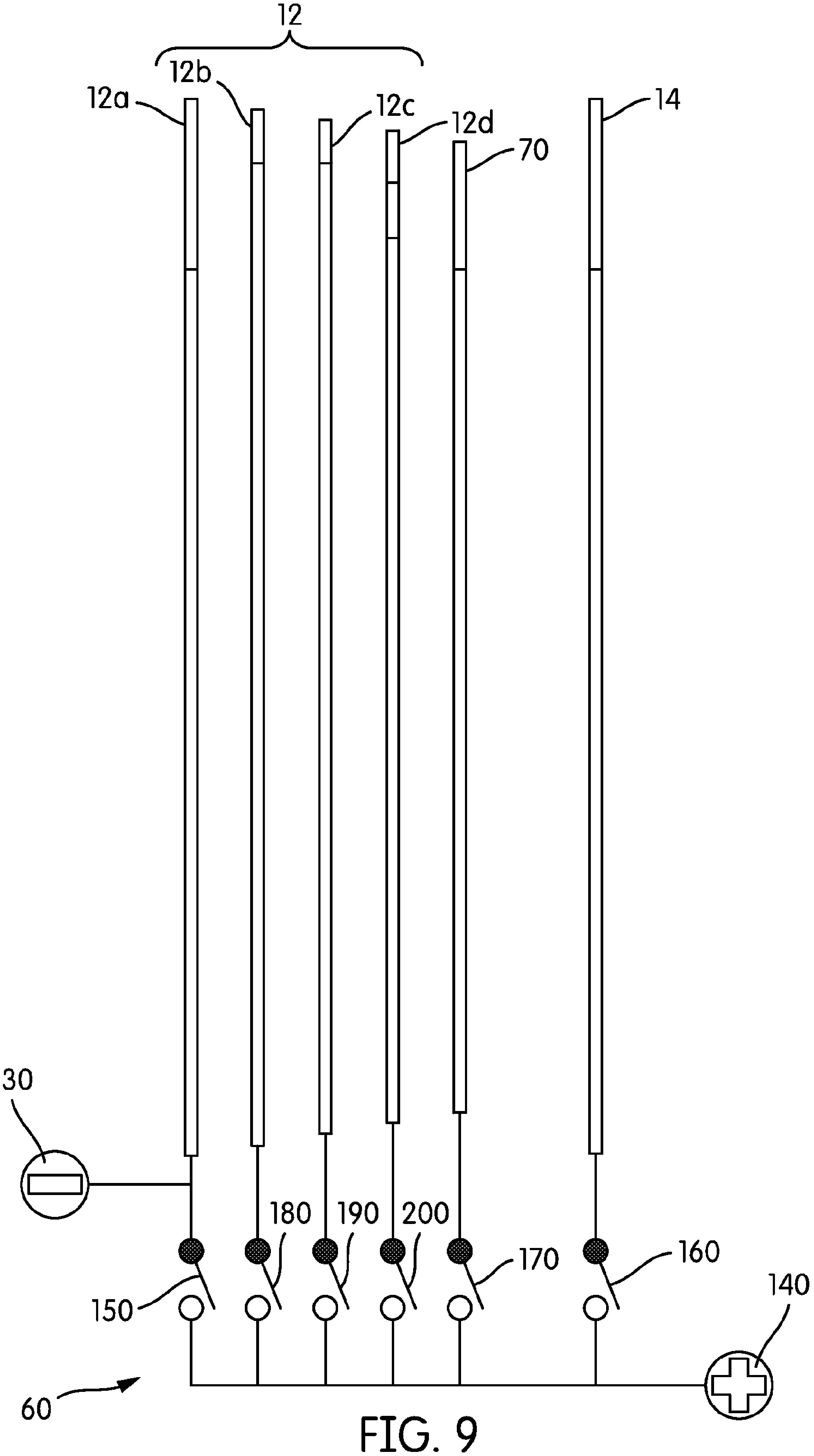


FIG. 9

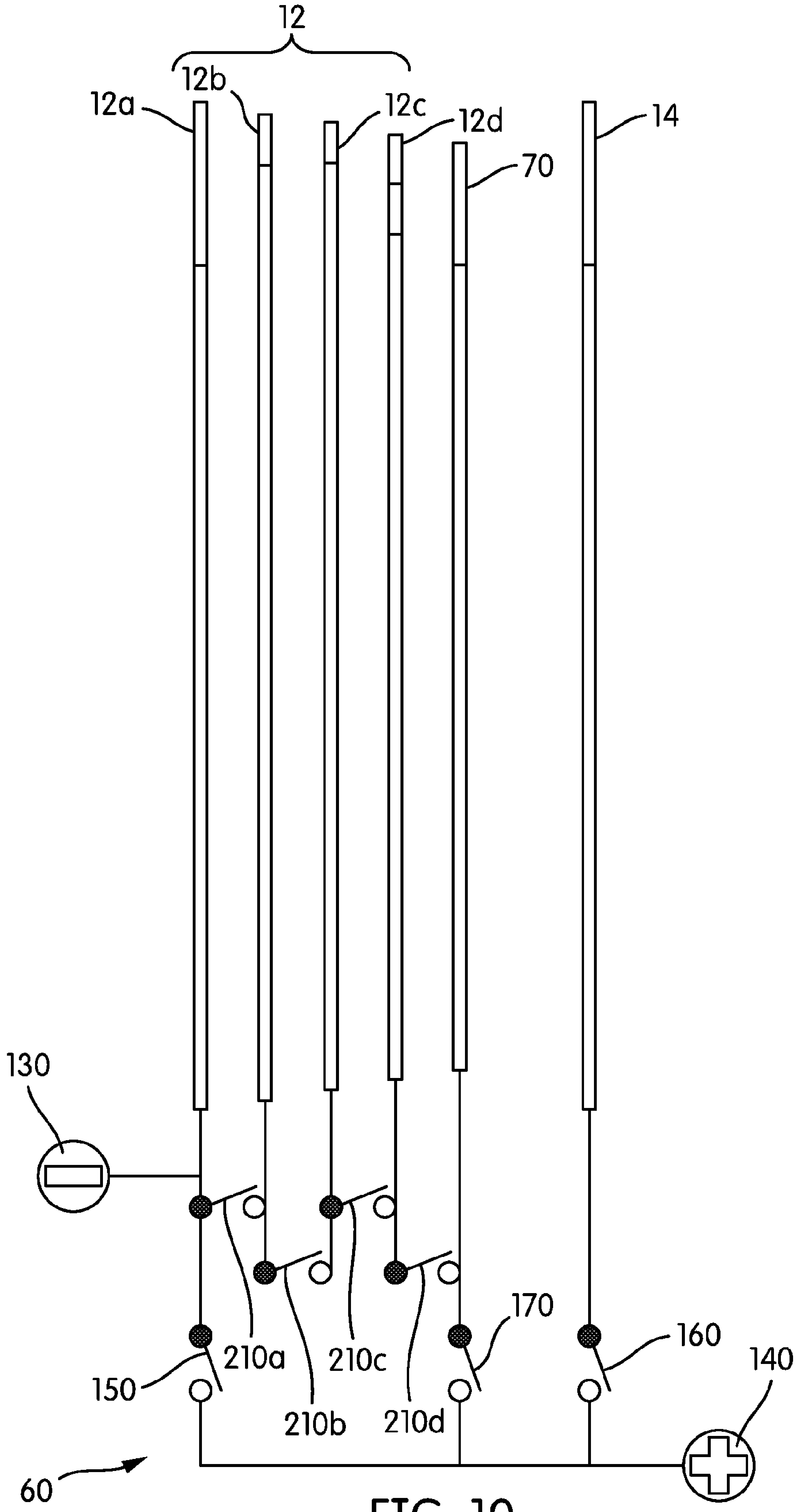

12
12a
12b
12c
12d
70
14
130
210a
210c
150
210b
210d
170
160
140
60

FIG. 10

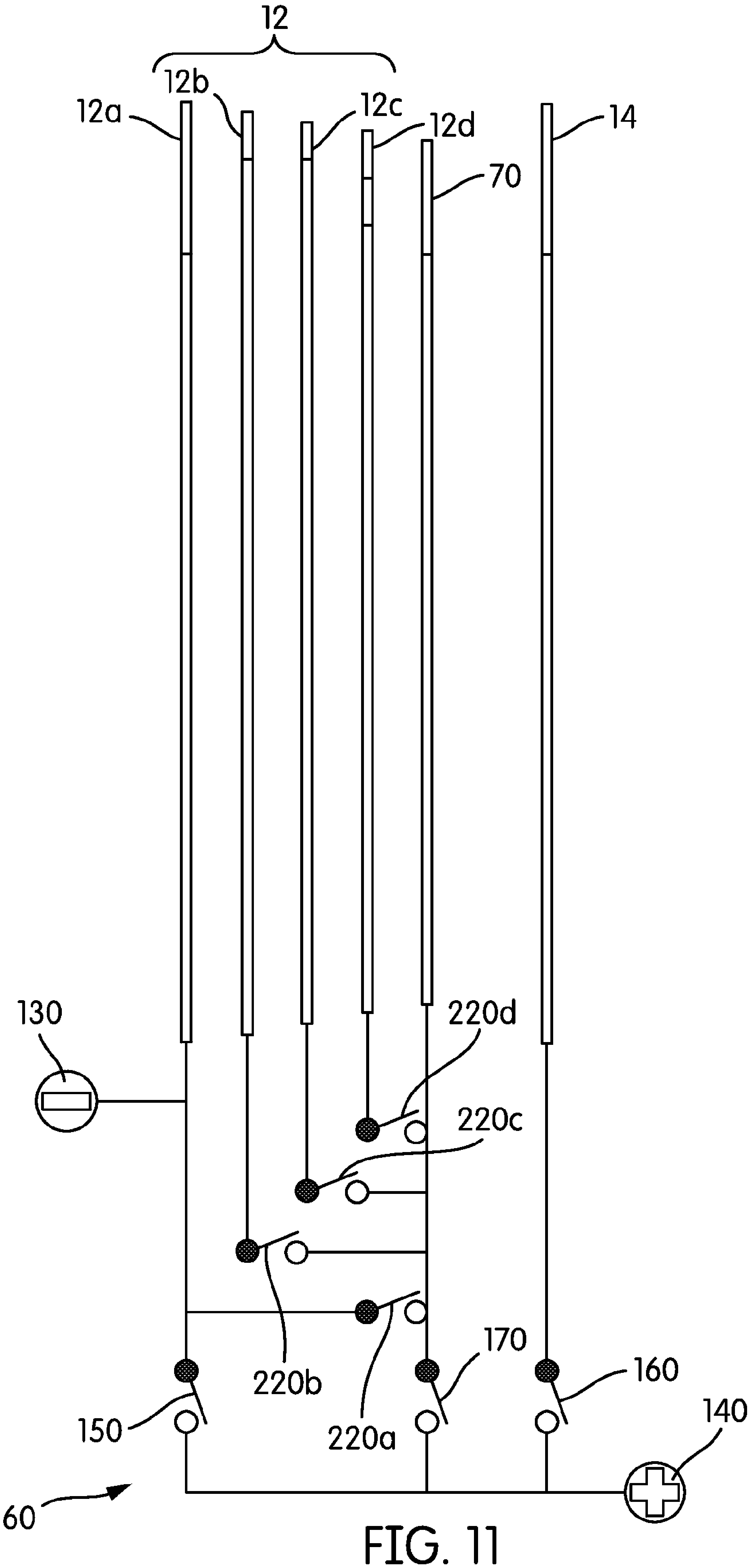

12
12b
12a
12c
12d
14
70
130
220d
220c
220b
220a
170
160
150
140
60

FIG. 11

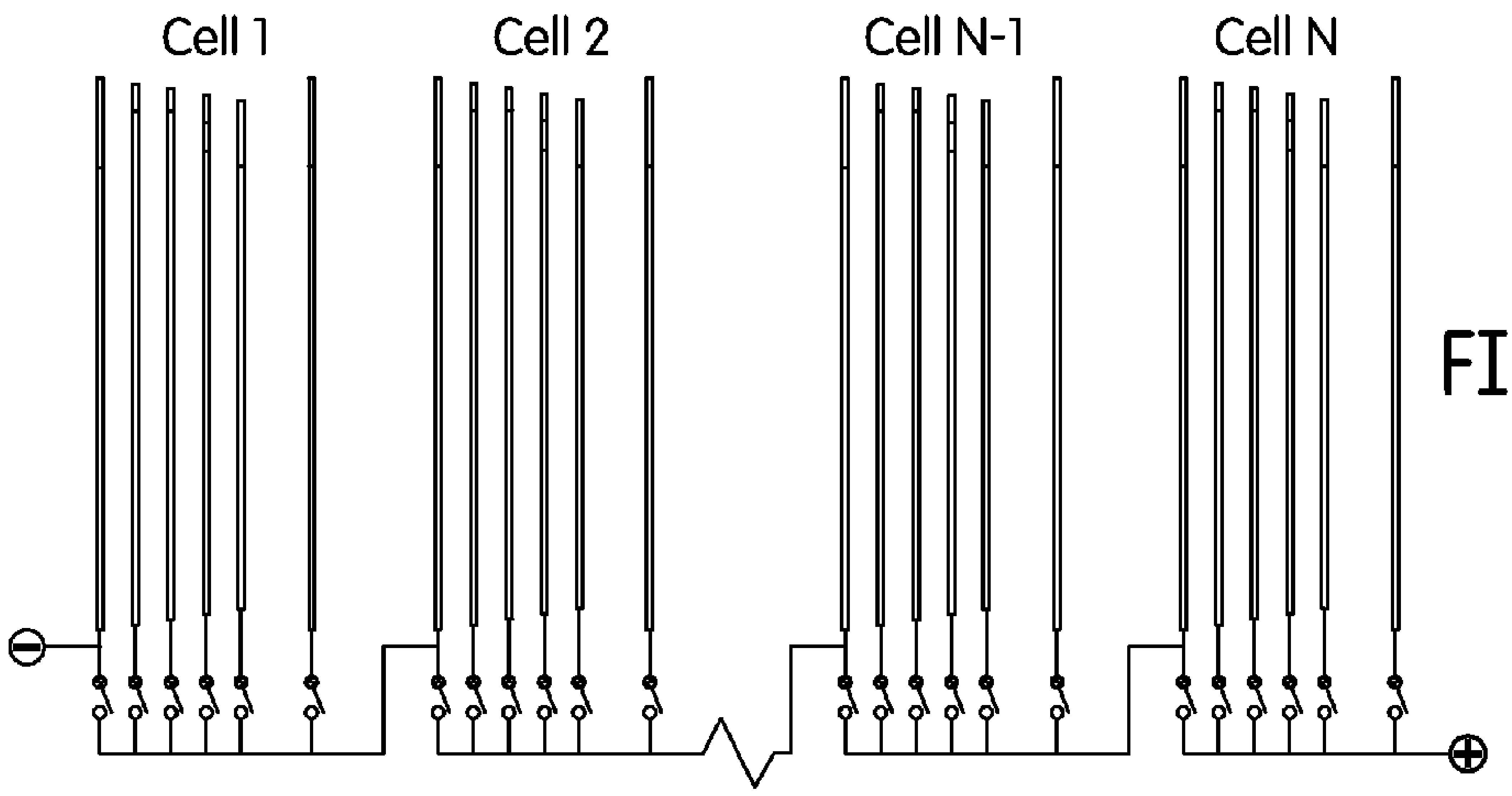


FIG. 12A

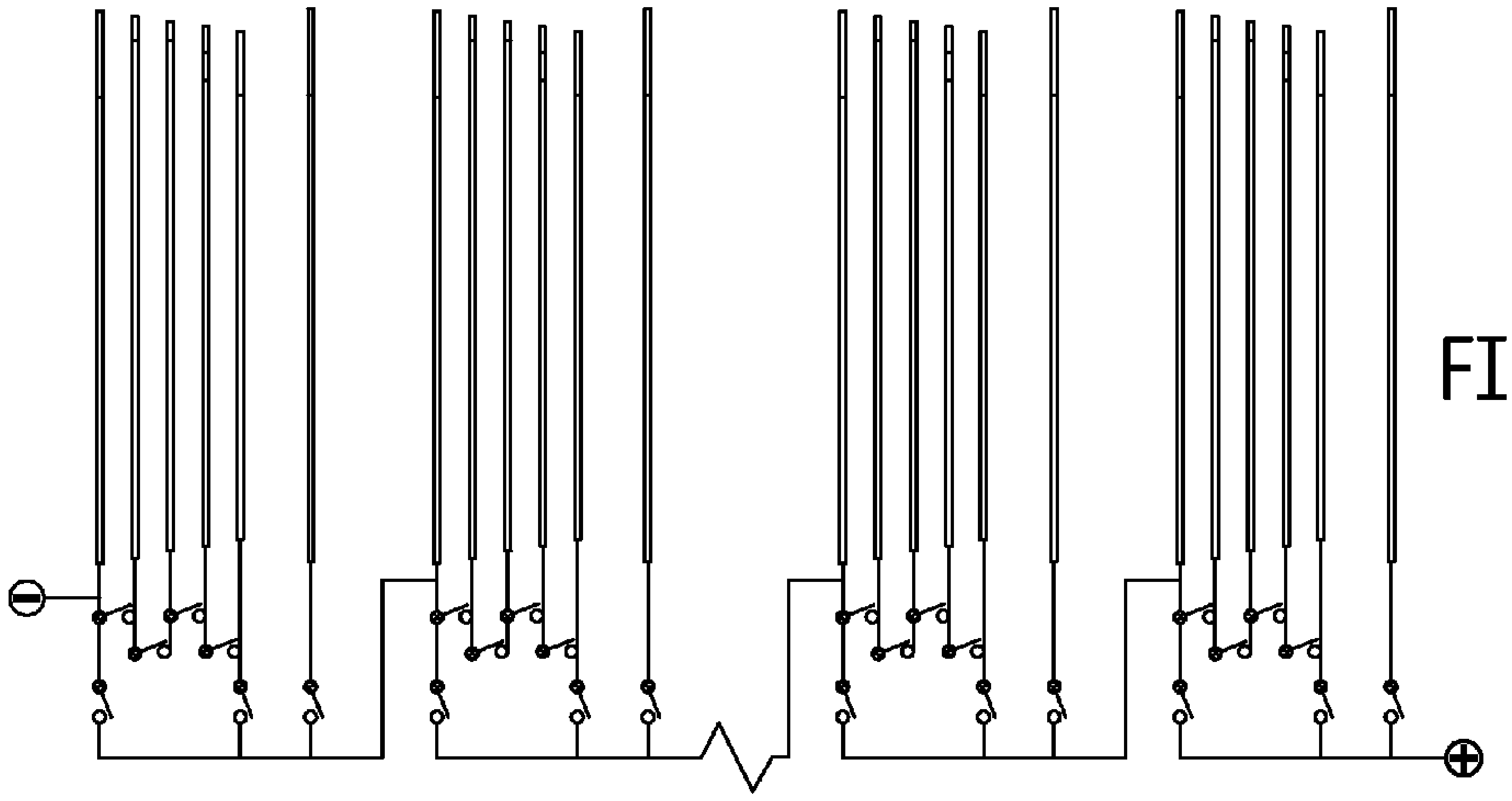


FIG. 12B

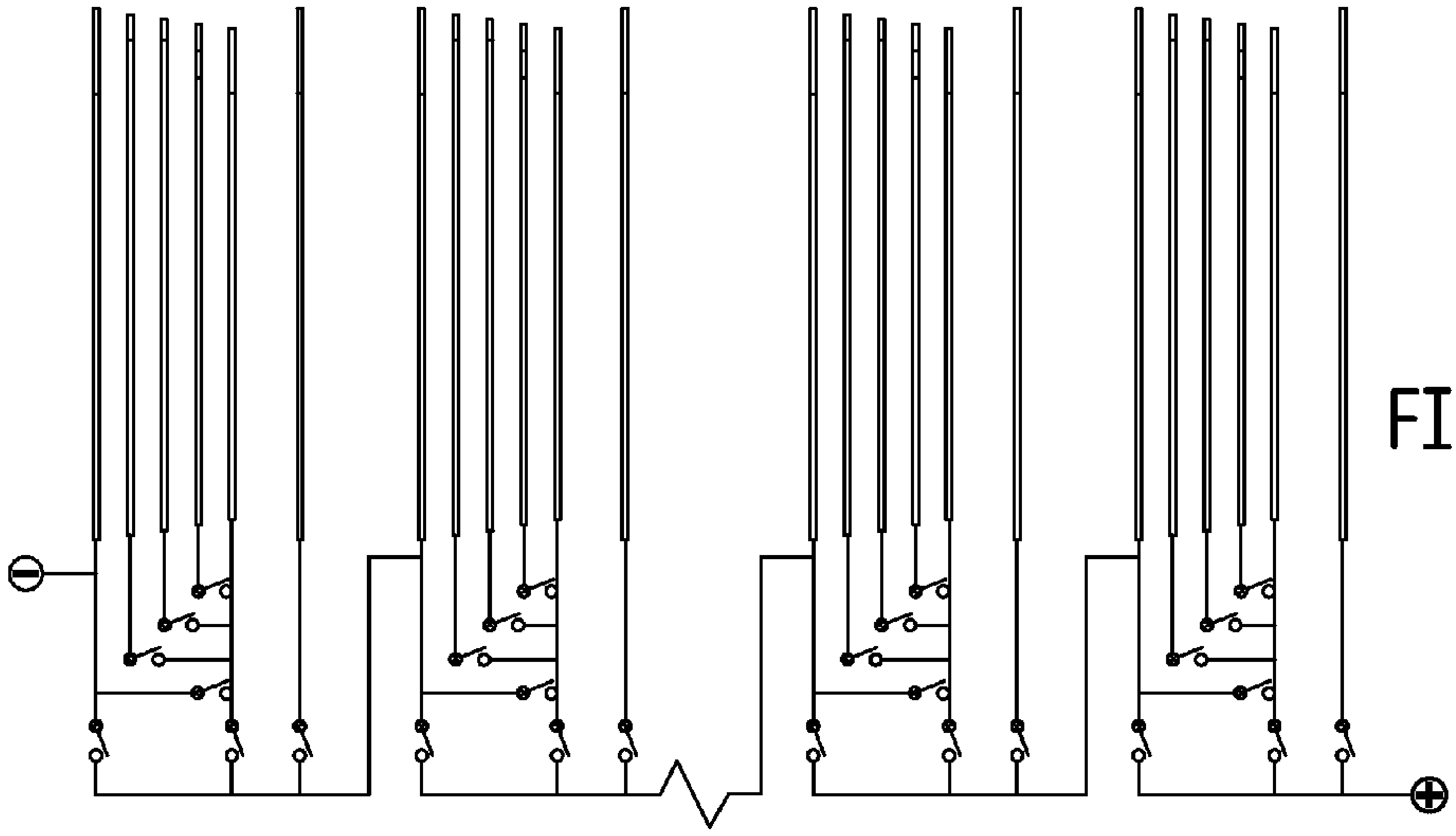


FIG. 12C

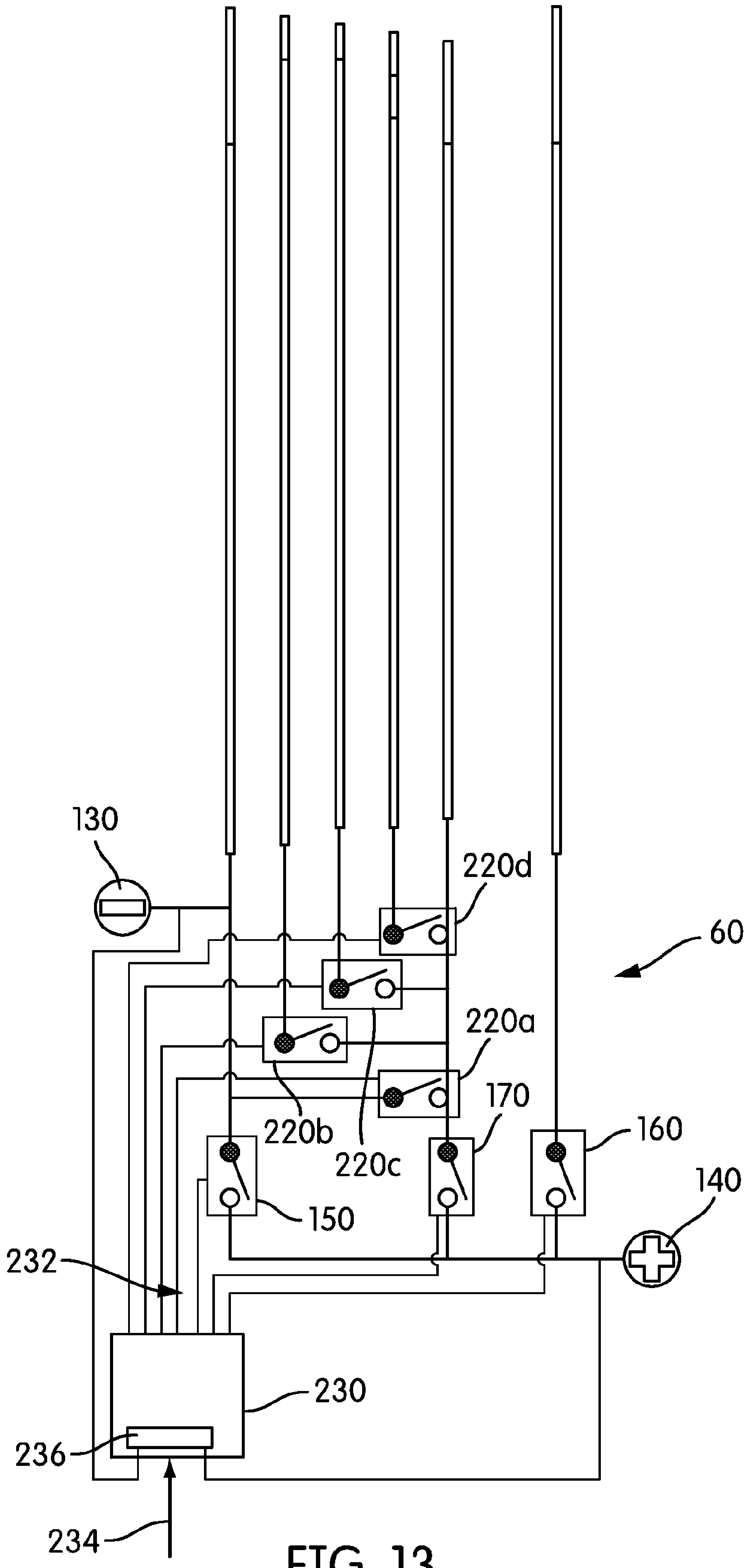


FIG. 13

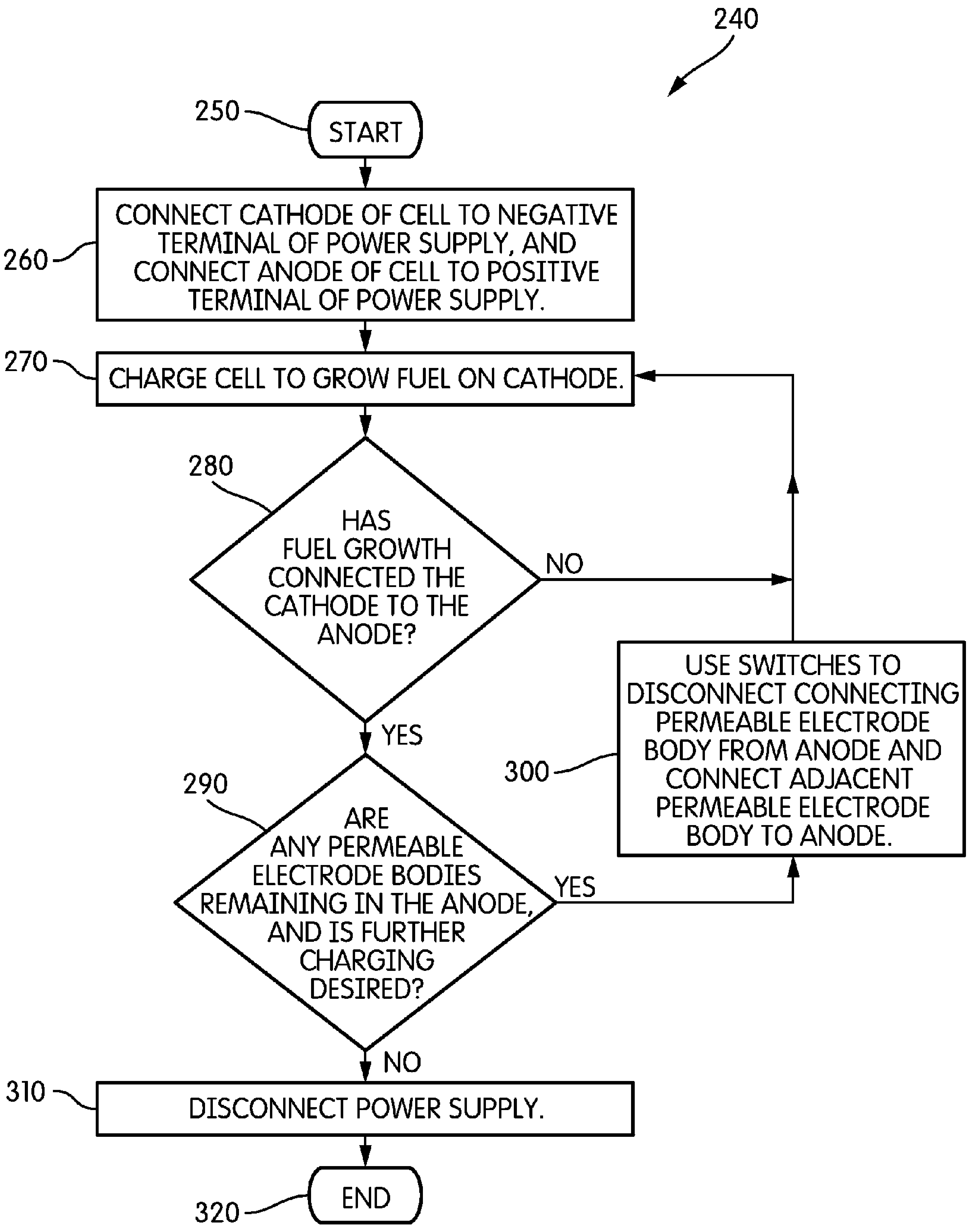

240
250
START
260
CONNECT CATHODE OF CELL TO NEGATIVE TERMINAL OF POWER SUPPLY, AND CONNECT ANODE OF CELL TO POSITIVE TERMINAL OF POWER SUPPLY.
270
CHARGE CELL TO GROW FUEL ON CATHODE.
280
HAS FUEL GROWTH CONNECTED THE CATHODE TO THE ANODE?
NO
YES
290
ARE ANY PERMEABLE ELECTRODE BODIES REMAINING IN THE ANODE, AND IS FURTHER CHARGING DESIRED?
YES
300
USE SWITCHES TO DISCONNECT CONNECTING PERMEABLE ELECTRODE BODY FROM ANODE AND CONNECT ADJACENT PERMEABLE ELECTRODE BODY TO ANODE.
NO
310
DISCONNECT POWER SUPPLY.
320
END

FIG. 14

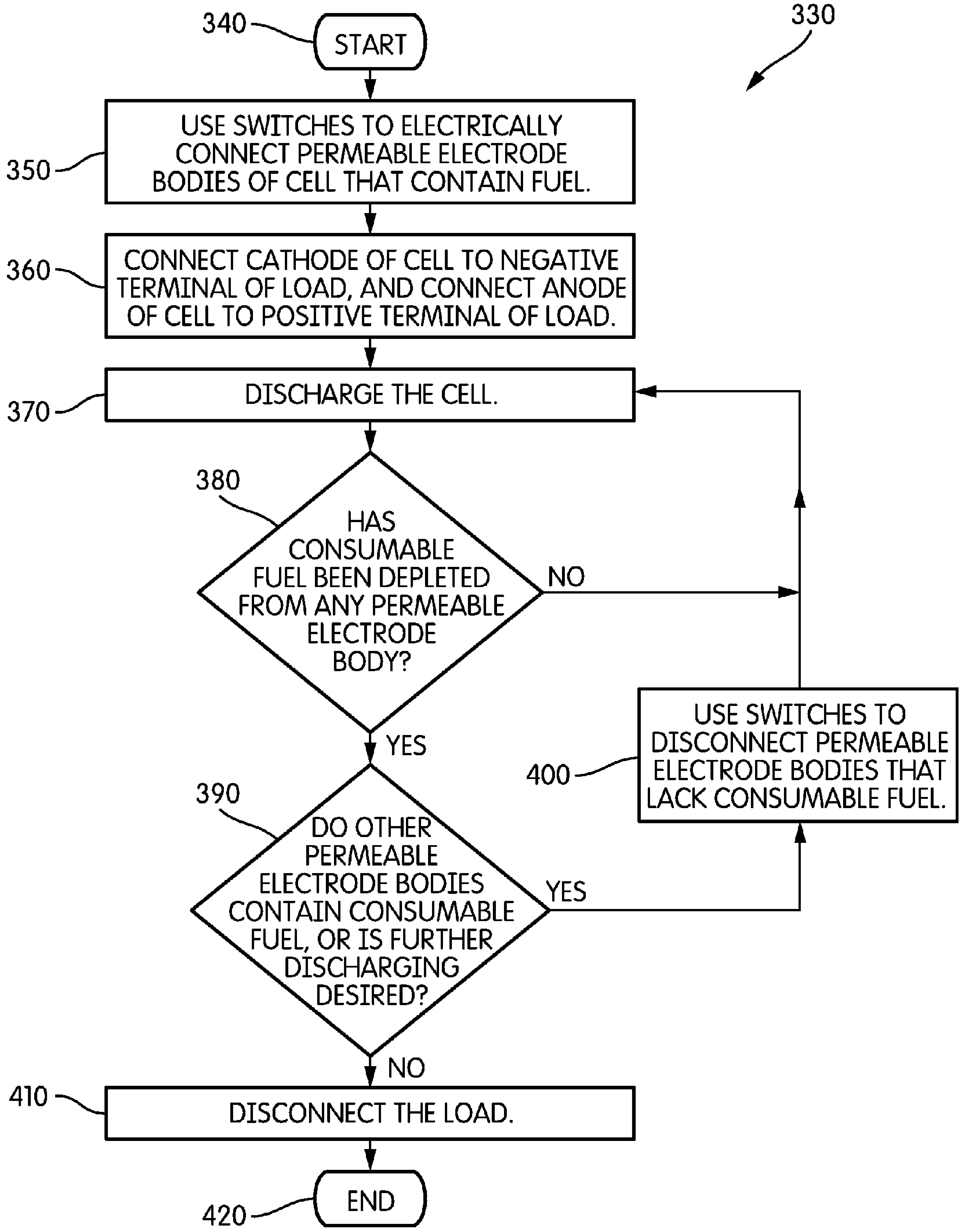

330
340
START
350
USE SWITCHES TO ELECTRICALLY CONNECT PERMEABLE ELECTRODE BODIES OF CELL THAT CONTAIN FUEL.
360
CONNECT CATHODE OF CELL TO NEGATIVE TERMINAL OF LOAD, AND CONNECT ANODE OF CELL TO POSITIVE TERMINAL OF LOAD.
370
DISCHARGE THE CELL.
380
HAS CONSUMABLE FUEL BEEN DEPLETED FROM ANY PERMEABLE ELECTRODE BODY?
NO
YES
390
DO OTHER PERMEABLE ELECTRODE BODIES CONTAIN CONSUMABLE FUEL, OR IS FURTHER DISCHARGING DESIRED?
YES
400
USE SWITCHES TO DISCONNECT PERMEABLE ELECTRODE BODIES THAT LACK CONSUMABLE FUEL.
NO
410
DISCONNECT THE LOAD.
420
END

FIG. 15

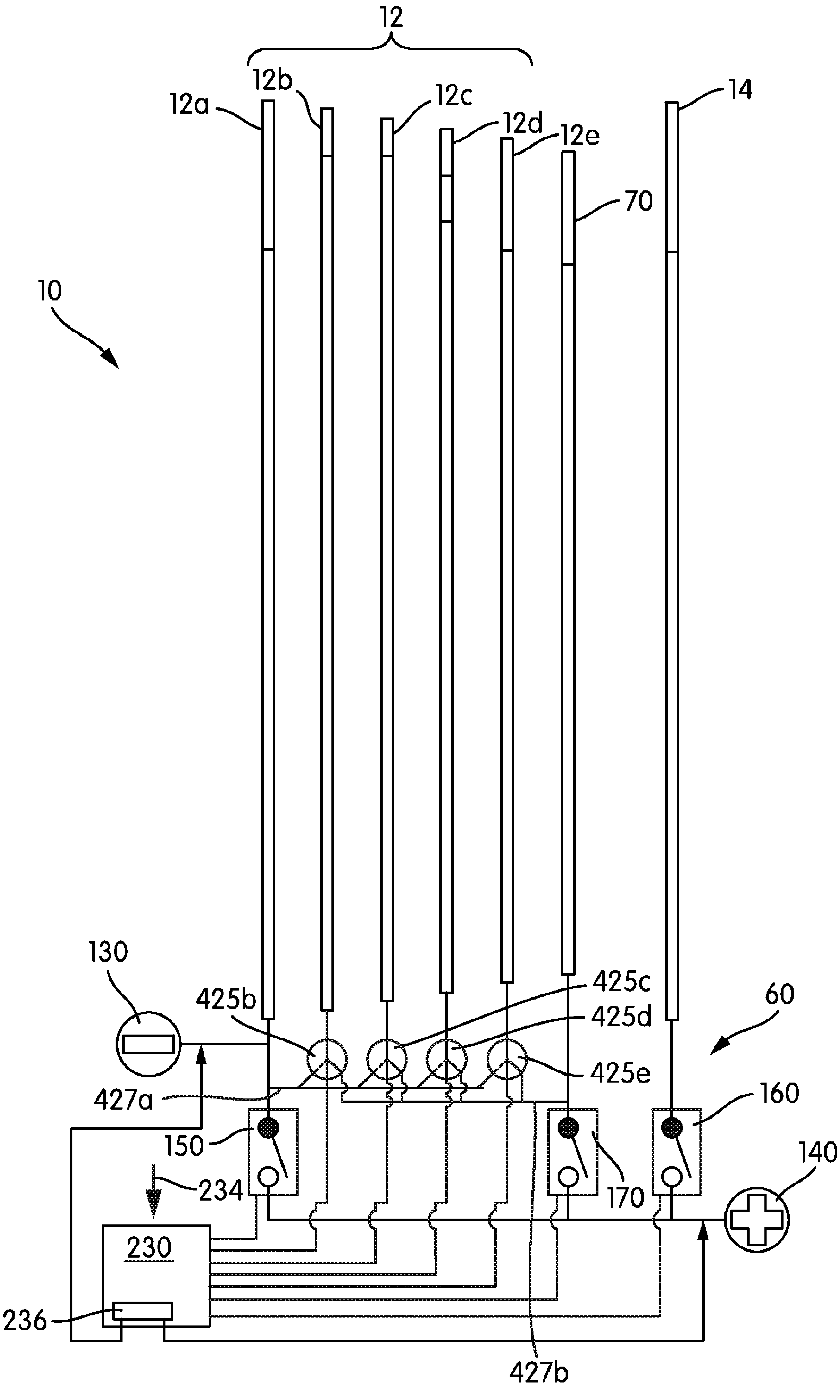

12
12a
12b
12c
12d
12e
14
70
10
130
425b
425c
425d
425e
60
427a
150
160
170
140
234
230
236
427b

FIG. 16

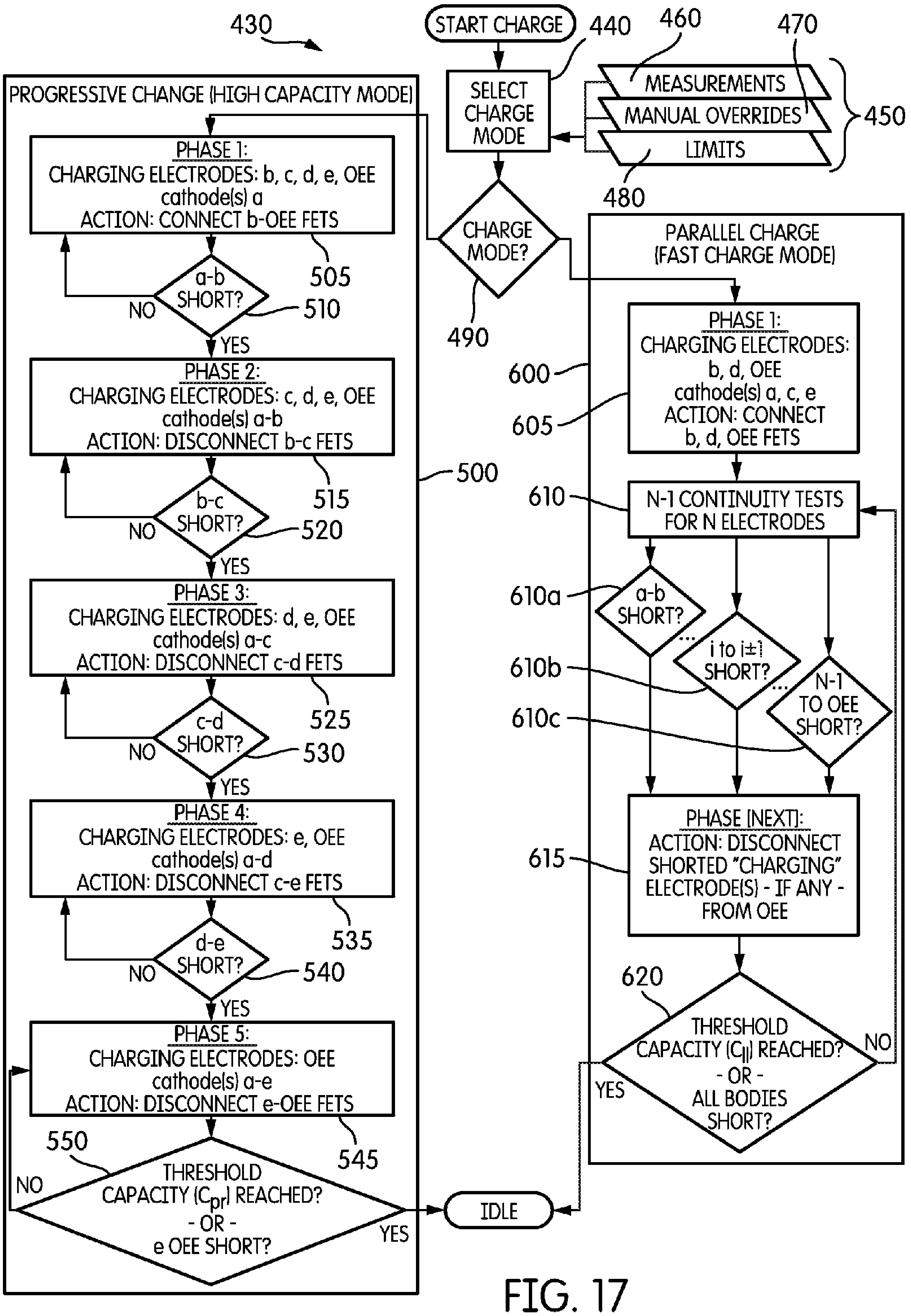

430
START CHARGE
440
460
470
SELECT CHARGE MODE
MEASUREMENTS
MANUAL OVERRIDES
LIMITS
450
480
PROGRESSIVE CHANGE (HIGH CAPACITY MODE)
PHASE 1: CHARGING ELECTRODES: b, c, d, e, OEE cathode(s) a ACTION: CONNECT b-OEE FETS
505
a-b SHORT?
NO
YES
510
PHASE 2: CHARGING ELECTRODES: c, d, e, OEE cathode(s) a-b ACTION: DISCONNECT b-c FETS
515
b-c SHORT?
NO
YES
520
PHASE 3: CHARGING ELECTRODES: d, e, OEE cathode(s) a-c ACTION: DISCONNECT c-d FETS
525
c-d SHORT?
NO
YES
530
PHASE 4: CHARGING ELECTRODES: e, OEE cathode(s) a-d ACTION: DISCONNECT c-e FETS
535
d-e SHORT?
NO
YES
540
PHASE 5: CHARGING ELECTRODES: OEE cathode(s) a-e ACTION: DISCONNECT e-OEE FETS
545
550
THRESHOLD CAPACITY (C_{pr}) REACHED? - OR - e OEE SHORT?
NO
YES
500
CHARGE MODE?
490
IDLE
PARALLEL CHARGE (FAST CHARGE MODE)
600
605
PHASE 1: CHARGING ELECTRODES: b, d, OEE cathode(s) a, c, e ACTION: CONNECT b, d, OEE FETS
610
N-1 CONTINUITY TESTS FOR N ELECTRODES
610a
a-b SHORT?
610b
i to i±1 SHORT?
610c
N-1 TO OEE SHORT?
615
PHASE (NEXT): ACTION: DISCONNECT SHORTED "CHARGING" ELECTRODE(S) - IF ANY - FROM OEE
620
THRESHOLD CAPACITY (C||) REACHED? - OR - ALL BODIES SHORT?
YES
NO

FIG. 17

MULTI-MODE CHARGING OF HIERARCHICAL ANODE

CROSS REFERENCE TO RELATED APPLICATIONS

The present application claims priority to U.S. Provisional Application Ser. No. 61/414,579 filed on Nov. 17, 2010, the entirety of which is incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates to a rechargeable electrochemical cell system.

BACKGROUND OF THE INVENTION

Electrochemical cells are well known. An electrochemical cell includes an anode or fuel electrode at which a fuel oxidation reaction takes place, a cathode or oxidant electrode at which an oxidant reduction reaction takes place, and an ionically conductive medium for supporting the transport of ions. In some metal-air cells, such as those disclosed in U.S. patent application Ser. No. 12/385,489 (published as U.S. Patent Application Publication No. 2009/0284229) and Ser. No. 12/901,410 (published as U.S. Patent Application Publication No. 2011/0086278), both of which are incorporated herein by reference, the fuel electrode comprises a plurality of scaffolded electrode bodies, on which metal fuel is reduced and electrodeposited.

Electrochemical cell systems may comprise a plurality of electrochemical cells. In some such electrochemical cell systems, the fuel electrode of the first cell may be coupled to a first terminal, the oxidant electrode of each cell within the cell system may be connected to the fuel electrode of the subsequent cell, and the oxidant electrode of the last cell in the series may be connected to a second terminal. Thus, a potential difference is created within each individual cell, and because these cells are coupled in series, a cumulative potential difference is generated between the first and second terminals. These terminals connect to a load L, creating a potential difference that drives current.

Among other things, the present application endeavors to provide a more efficient and effective architecture for recharging and discharging electrochemical cells and electrochemical cell systems.

SUMMARY OF THE INVENTION

According to an embodiment of the present disclosure, an electrochemical cell includes a fuel electrode comprising a series of permeable electrode bodies arranged in spaced apart relation, an oxidant electrode spaced apart from the fuel electrode, and a charging electrode selected from the group consisting of (a) the oxidant electrode, (b) a third electrode spaced from the fuel electrode and the oxidant electrode, and (c) a portion of the fuel electrode. The electrochemical cell further includes an ionically conductive medium contacting the electrodes, and a charge/discharge controller coupled to a plurality of the electrode bodies of the fuel electrode. The charge/discharge controller is configured to apply an electrical current between the charging electrode and at least one of the permeable electrode bodies, with the charging electrode functioning as an anode and the at least one permeable electrode body functioning as a cathode, such that reducible metal fuel ions in the ionically conductive medium are reduced and electrodeposited as metal fuel in oxidizable form on the at least one permeable electrode body, so that said electrodeposition causes growth of the metal fuel among the permeable electrode bodies, with the electrodeposited metal fuel establishing an electrical connection between the permeable electrode bodies. The charge/discharge controller is configured to selectively apply the electrical current to a different number of said permeable electrode bodies, each functioning as a cathode, based on at least one input parameter so as to adjust a rate and density of the growth of the electrodeposited metal fuel.

According to another embodiment of the present disclosure, a method of recharging an electrochemical cell is provided. The electrochemical cell includes a fuel electrode comprising a series of permeable electrode bodies arranged in spaced apart relation, an oxidant electrode spaced apart from the fuel electrode, and a charging electrode selected from the group consisting of (a) the oxidant electrode, (b) a third electrode spaced from the fuel electrode and the oxidant electrode, and (c) a portion of the fuel electrode. The electrochemical cell further includes an ionically conductive medium contacting the electrodes, and a charge/discharge controller coupled to a plurality of the electrode bodies of the fuel electrode. The charge/discharge controller is configured to apply an electrical current between the charging electrode and at least one of the permeable electrode bodies, with the charging electrode functioning as an anode, and the at least one permeable electrode body functioning as a cathode, such that reducible metal fuel ions in the ionically conductive medium are reduced and electrodeposited as metal fuel in oxidizable form on the at least one permeable electrode body, so that said electrodeposition causes growth of the metal fuel among the permeable electrode bodies with the electrodeposited metal fuel establishing an electrical connection between the permeable electrode bodies. The charge/discharge controller is configured to selectively apply the electrical current to a different number of said permeable electrode bodies based on at least one input parameter so as to adjust a rate and density of the growth of the electrodeposited metal fuel.

The method includes selecting, based on the at least one input parameter, between a higher density progressive growth mode and a higher rate growth mode. The method further includes charging the electrochemical cell based on the selected one of the higher density progressive charge mode and the higher rate growth mode. In the higher density progressive growth mode, said charging comprises applying the electrical current to a terminal one of the permeable electrode bodies, with the charging electrode functioning as the anode and the terminal electrode body functioning as the cathode, such that the reducible metal fuel ions are reduced and electrodeposited as metal fuel in oxidizable form on the terminal permeable electrode body. The electrodeposition causes growth of the metal fuel among the permeable electrode bodies such that the electrodeposited metal fuel establishes an electrical connection between the terminal electrode body and each subsequent permeable electrode body with said reduction and deposition occurring on each subsequent permeable electrode body upon establishment of said electrical connection. In the higher rate growth mode, said charging comprises applying the electrical current simultaneously to a plurality of said electrode bodies, with the charging electrode functioning as the anode and each of the plurality of electrode bodies functioning as cathodes, such that the reducible metal fuel ions are reduced and electrodeposited as metal fuel in oxidizable form on the terminal permeable electrode body, said electrodeposition causing growth of the metal fuel among the permeable electrode bodies. The method further includes disconnecting the electrical current to discontinue the charging.

Other objects, features, and advantages of the present invention will become apparent from the following detailed description, the accompanying drawings, and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates a cross-sectional view of an electrochemical cell system that includes two electrochemical cells;

FIG. **2** illustrates an exploded view of the electrochemical cell system of FIG. **1**;

FIG. **3** illustrates an electrode holder of one of the electrochemical cells of FIG. **1**;

FIG. **4** illustrates the electrode holder of FIG. **3**, holding a fuel electrode and a plurality of spacers connected to the electrode holder

FIG. **5** illustrates one of the spacers of FIG. **4** in greater detail;

FIG. **6** illustrates a connection between the spacers of FIG. **5** and the electrode holder of FIG. **3** in greater detail;

FIG. **7** schematically illustrates electrical connections between the electrochemical cell and an external load or power supply according to an embodiment of a cell system in accordance with the present invention;

FIG. **8** schematically illustrates electrical connections between the electrochemical cell and an external load or power supply according to an embodiment of a cell system in accordance with the present invention;

FIG. **9** schematically illustrates a switching system according to an embodiment of the cell system of FIG. **8**;

FIG. **10** schematically illustrates a switching system according to another embodiment of the cell system of FIG. **8**;

FIG. **11** schematically illustrates a switching system according to another embodiment of the cell system of FIG. **8**;

FIGS. **12**A-C schematically illustrate the embodiments of FIGS. **9**-**11** further comprising a plurality of cells a switching system according to another embodiment of the cell of FIG. **8**;

FIG. **13** schematically illustrates a switching system similar to the embodiment of FIG. **11**, further comprising a controller;

FIG. **14** shows a flowchart illustrating an embodiment of a method of charging the cell, in accordance with the present invention;

FIG. **15** shows a flowchart illustrating an embodiment of a method of discharging the cell;

FIG. **16** schematically illustrates a switching system according to another embodiment of the cell of FIG. **8**; and,

FIG. **17** shows a flowchart illustrating an embodiment of an algorithm for charging the cell, in accordance with the present invention.

DETAILED DESCRIPTION OF THE ILLUSTRATED EMBODIMENTS OF THE INVENTION

FIGS. **1** and **2** illustrate an electrochemical cell system **100** that includes two electrochemical cells **10** according to an embodiment of the invention. As illustrated, each cell **10** includes a fuel electrode **12**, and an oxidant electrode **14** that is spaced from the fuel electrode **12**. The fuel electrode **12** supported by an electrode holder **16**. The electrochemical system **100** also includes a cover **19** that is used to cover the electrochemical cells **10** on one side of the system **100**, while one of the electrode holders **16** is used to cover the opposite side of the system **100**, as illustrated in FIG. **1**.

In an embodiment, the fuel electrode **12** is a metal fuel electrode that functions as an anode when the cell **10** operates in discharge, or electricity generating, mode, as discussed in further detail below. In an embodiment, the fuel electrode **12** may comprise a plurality of permeable electrode bodies **12***a*-*d*, such as screens that are made of any formation able to capture and retain, through electrodepositing, or otherwise, particles or ions of metal fuel from an ionically conductive medium that circulates in the cell **10**, as discussed in further detail below. Components of the cell **10**, including for example, the fuel electrode **12**, the permeable electrode bodies **12***a*-*d* thereof, and the oxidant electrode **14**, may be of any suitable construction or configuration, including but not limited to being constructed of Nickel or Nickel alloys (including Nickel-Cobalt, Nickel-Iron, Nickel-Copper (i.e. Monel), or superalloys), Copper or Copper alloys, brass, bronze, or any other suitable metal. In an embodiment, a catalyst film may be applied to some or all of the permeable electrode bodies **12***a*-*d* and/or the oxidant electrode **14**, and have a high surface material that may be made of some of the materials described above. In an embodiment, the catalyst film may be formed by techniques such as thermal spray, plasma spray, electrodeposition, or any other particle coating method.

The fuel may be a metal, such as iron, zinc, aluminum, magnesium, or lithium. By metal, this term is meant to encompass all elements regarded as metals on the periodic table, including but not limited to alkali metals, alkaline earth metals, lanthanides, actinides, and transition metals, either in atomic, molecular (including metal hydrides), or alloy form when collected on the electrode body. However, the present invention is not intended to be limited to any specific fuel, and others may be used. The fuel may be provided to the cell **10** as particles suspended in the ionically conductive medium. In some embodiments, a metal hydride fuel may be utilized in cell **10**.

The ionically conductive medium may be an aqueous solution. Examples of suitable mediums include aqueous solutions comprising sulfuric acid, phosphoric acid, triflic acid, nitric acid, potassium hydroxide, sodium hydroxide, sodium chloride, potassium nitrate, or lithium chloride. The medium may also use a non-aqueous solvent or an ionic liquid. In the non-limiting embodiment described herein, the medium is aqueous potassium hydroxide. In an embodiment, the ionically conductive medium may comprise an electrolyte. For example, a conventional liquid or semi-solid electrolyte solution may be used, or a room temperature ionic liquid may be used, as mentioned in U.S. patent application Ser. No. 12/776,962 (published as U.S. Patent Application Publication No. 2010/0285375), the entirety of which is incorporated herein. In an embodiment where the electrolyte is semi-solid, porous solid state electrolyte films (i.e. in a loose structure) may be utilized.

The fuel may be oxidized at the fuel electrode **12** when the fuel electrode **12** is operating as an anode, and an oxidizer, such as oxygen, may be reduced at the oxidant electrode **14** when the oxidant electrode **14** is operating as a cathode, which is when the cell **10** is connected to a load L and the cell **10** is in discharge or electricity generation mode, as discussed in further detail below. The reactions that occur during discharge mode may generate by-product precipitates, e.g., a reducible fuel species, in the ionically conductive medium. For example, in embodiments where the fuel is zinc, zinc oxide may be generated as a by-product precipitate/reducible fuel species. The oxidized zinc or other metal may also be supported by, oxidized with or solvated in the electrolyte solution, without forming a precipitate (e.g. zincate may be a dissolved reducible fuel species remaining in the fuel). During a recharge mode, which is discussed in further detail below, the reducible fuel species, e.g., zinc oxide, may be reversibly reduced and deposited as the fuel, e.g., zinc, onto at least a portion of the fuel electrode **12** that functions as a cathode during recharge mode. During recharge mode, either the oxidant electrode **14** or a separate charging electrode **70** (which may be of similar construction or configuration as permeable electrode bodies **12***a-d* in some embodiments), and/or another portion of the fuel electrode **12**, as described below, functions as the anode. The switching between discharge and recharge modes is discussed in further detail below.

The electrode holder **16** defines a cavity **18** in which the fuel electrode **12** is held. The electrode holder **16** also defines an inlet **20** and an outlet **22** for the cell **10**. The inlet **20** is configured to allow the ionically conductive medium to enter the cell **10** and/or recirculate through the cell **10**. The inlet **20** may be connected to the cavity **18** via an inlet channel **24**, and the outlet **22** may be connected to the cavity **18** via an outlet channel **26**. As illustrated in FIG. **3**, the inlet channel **24** and the outlet channel **26** may each provide a meandering tortuous path through which the ionically conductive medium may flow. The meandering path defined by the inlet channel **24** preferably does not include any sharp corners in which the flow of the medium may become stagnated or in which any particulates in the medium may collect. As discussed in further detail below, the length of the channels **24**, **26** may be designed to provide an increased ionic resistance between cells that are fluidly connected in series.

For each cell **10**, a permeable seal member **17** may be bonded between sealing surfaces on the electrode holders **16** and/or the cover **19**, as appropriate, to enclose at least the fuel electrode **12** in the cavity **18**. The seal member **17** also covers the inlet and outlet channels **24**, **26**. The seal member **17** is non-conductive and electrochemically inert, and is preferably designed to be permeable to the ionically conductive medium in the orthogonal direction (i.e., through its thickness), without permitting lateral transport of the ionically conductive medium. This enables the ionically conductive medium to permeate through the seal member **17** for enabling ion conductivity with the oxidant electrode **14** on the opposing side to support the electrochemical reactions, without "wicking" the ionically conductive medium laterally outwardly from the cell **10**. A few non-limiting examples of a suitable material for the seal member **17** are EPDM and TEFLON®.

In the illustrated embodiment, the cavity **18** has a generally rectangular, or square, cross-section that substantially matches the shape of the fuel electrode **12**. The cavity **18** may be connected to the inlet channel **24** by a plurality of inlets **34** so that when the ionically conductive medium and precipitates or reducible fuel species enter the cavity **18**, the ionically conductive medium and fuel are distributed along a side of the fuel electrode **12**. In some embodiments, one side of the cavity **18**, specifically, the side of the cavity **18** that is connected to the inlet channel **24**, may include a plurality of fluidization zones, such as is described in U.S. patent application Ser. No. 12/901,410, incorporated herein in its entirety by reference. In other embodiments, the ionically conductive medium may enter the cavity **18** through a diffuser, such as is described in U.S. Provisional Patent Application No. 61/301,377, now converted into U.S. patent application Ser. No. 13/019,923 (published as U.S. Patent Application Publication No. 2011/0189551), each of which is also incorporated herein in its entirety by reference. In various embodiments, the ionically conductive medium may flow in parallel or in series through a plurality of cells **10**. In some embodiments, the ionically conductive medium may utilize a combination of parallel and series flows. Furthermore, in various embodiments the ionically conductive medium may flow at a varying rate, and even may flow intermittently (i.e. static for a time) during operation of the one or more cells **10**.

As illustrated in FIG. **4**, a plurality of spacers **40**, each of which extends across the fuel electrode **12** in a spaced relation to each other, may be connected to the electrode holder **16** so that the fuel electrode **12** may be held in place relative to the electrode holder **16** and to the oxidant electrode **14**. In an embodiment, the plurality of permeable electrode bodies **12***a*-**12***d*, as illustrated in FIG. **2**, may be separated by sets of the plurality of spacers **40**, so that each set of spacers **40** is positioned in between adjacent electrode bodies to electrically isolate the electrode bodies **12***a*-**12***d* from each other. Within each set of spacers **40** between adjacent electrode bodies, the spacers **40** are positioned in a spaced relation in a manner that creates so-called "flow lanes" **42** therebetween, as discussed in greater detail below. The flow lanes **42** are three-dimensional and have a height that is substantially equal to the height of the spacers **40**. In an embodiment, the spacers **40** may be provided by a single frame that has cutouts corresponding to the flow lanes. In an embodiment, the flow lanes **42** may include a foam or honeycomb-type structure that is configured to allow the ionically conductive medium to flow therethrough. In an embodiment, the flow lanes **42** may include an array of pins that are configured to disrupt the flow of the ionically conductive medium through the flow lanes. In an embodiment, the frame, spacers **40**, flow lanes **42**, and/or other elements of cell **10** may be defined by plastic formed by injection molding, or epoxy/insulating material formed using chemical processes. The illustrated embodiment is not intended to by limiting in any way.

The spacers **40** are non-conductive and electrochemically inert so they are inactive with regard to the electrochemical reactions in the cell **10**. The spacers **40** are preferably sized so that when they are connected to the electrode holder **16**, the spacers **40** are in tension, which allows the spacers **40** to press against the fuel electrode **12**, or one of the electrode bodies **12***a*-**12***c*, so as to hold the fuel electrode **12** or bodies thereof in a flat relation relative to the electrode holder **16**. The spacers **40** may be made from a plastic material, such as polypropylene, polyethylene, noryl, fluoropolymer, etc. that allows the spacers **40** to be connected to the electrode holder **16** in tension. In various embodiments, the spacers **40** may be attached together by techniques such as (but not limited to) thermal bonding, chemical bonding, or ultrasonic welding/bonding

In the embodiment illustrated in FIG. **5**, each spacer has an elongated middle portion **44**, and a shaped connecting portion **46** at each end. The shaped connecting portions **46** are configured to be held by openings **48** having substantially similar shapes in the electrode holder **16**, as illustrated in FIG. **6**. In the illustrated embodiment, the shaped portions **46** and the openings **48** have a substantially triangular shape, although the illustrated shape is not intended to be limiting in any way. The substantially triangular shape provides surfaces **50** on opposite sides of the elongated portion **44** of the spacer **40** that are configured to contact corresponding surfaces **52** on the electrode holder **16**. Because the surfaces **50**, **52** are angled with respect to a major axis MA of the elongated portion **44** of the spacer **40** and the tension in the spacer **40** will be along the major axis MA, the forces created by the tension may be distributed across a larger surface, as compared to a shaped portion having a circular or square shape with the same area.

Once the spacers **40** have been connected to the electrode holder **16** via the end portions **46**, the flow lanes **42** are defined across the cavity **18** of the electrode holder **16**. The spacers **40** are configured to essentially seal off one flow lane **42***a* from an adjacent flow lane **42***b*, that is separated by one of the spacers **40** so that the ionically conductive medium is guided to generally flow in substantially one direction. Specifically, the ionically conductive medium may generally flow in a first direction FD across the fuel electrode **12**, from the inlet channel **24** to the outlet channel **26**. A suitable pressure drop is generated between the inlet channel **24** and the inlets **34** so that the ionically conductive medium may flow across the cavity **18** and to the outlet channel **26**, even when the cell **10** is oriented such that the flow is substantially upward and against gravity. In an embodiment, the ionically conductive medium may also permeate through the fuel electrode **12**, or an individual permeable electrode body **12***a*-**12***d*, in a second direction SD and into a flow lane that is on the opposite side of the fuel electrode **12** or permeable electrode body **12***a*-**12***d*.

As illustrated in the embodiment of FIG. **7**, the fuel electrode **12** of cell **10** in electrochemical cell system **100** may be selectively connected to an external load L so that electrons given off by the fuel as the fuel is oxidized at the fuel electrode **12** may flow to the external load L. A switching system **60** comprising a plurality of switches, may selectively electrically connect each of the individual permeable electrode bodies **12***a*-**12***d* of the fuel electrode **12**, and may also selectively connect the permeable electrode bodies **12***a*-**12***d* to the oxidant electrode **14**. As shown, in some embodiments electrochemical cell system **100** may further comprise other cells **10**. In an embodiment, the switching system **60** may comprise a terminal selector system **62** configured to couple or decouple the external load L for use in discharging the cell **10**, or couple or decouple a power supply PS for use in charging the cell **10**. In another embodiment the switching system **60** and the terminal selector system **62** may be separate, but may, in an embodiment, communicate with each other. The switching system **60** is discussed in greater detail below.

The oxidant electrode **14** functions as a cathode when the oxidant electrode **14** is connected to the external load L and the cell **10** operates in discharge mode. When functioning as a cathode, the oxidant electrode **14** is configured to receive electrons from the external load L and reduce an oxidizer that contacts the oxidant electrode **14**. The oxidizer may be any species of the oxidant available for oxidation at the charging electrode. For example, the species may be a free ion, or an ion bonded to or coordinated with other ions or constituents in the ionically conductive medium. In an embodiment, the oxidant electrode **14** comprises an air breathing electrode and the oxidizer comprises oxygen in the surrounding air.

The oxidizer may be delivered to the oxidant electrode **14** by a passive transport system. For example, where oxygen present in ambient air is the oxidizer, simply exposing the oxidant electrode **14** to ambient air via openings in the cell, such as the openings that are provided by grooves **54** in the cover **19** and grooves **56** in the electrode holder **16** provided in the center of the electrochemical cell system **100**, may be sufficient to allow diffusion/permeation of oxygen into the oxidant electrode **14**. Other suitable oxidizers may be used and embodiments described herein are not limited to the use of oxygen as the oxidizer. A peripheral gasket **15** may be positioned between the periphery of the oxidant electrode **14** and the cover **19** or electrode holder **16**, as appropriate, to prevent the ionically conductive medium from leaking around the oxidant electrode **14** and into the area in the grooves **54**, **56** for air exposure.

In other embodiments, a pump, such as an air blower, may be used to deliver the oxidizer to the oxidant electrode **14** under pressure. The oxidizer source may be a contained source of oxidizer. In an embodiment, the oxygen may be recycled from the cell **10**, such as is disclosed in U.S. patent application Ser. No. 12/549,617 (published as U.S. Patent Application Publication No. 2010/0119895), incorporated in its entirety herein by reference. Likewise, when the oxidizer is oxygen from ambient air, the oxidizer source may be broadly regarded as the delivery mechanism, whether it be passive or active (e.g., pumps, blowers, etc.), by which the air is permitted to flow to the oxidant electrode **14**. Thus, the term “oxidizer source” is intended to encompass both contained oxidizers and/or arrangements for passively or actively delivering oxygen from ambient air to the oxidant electrode **14**.

Electricity that can be drawn by the external load L is generated when the oxidizer at the oxidant electrode **14** is reduced, while the fuel at the fuel electrode **12** is oxidized to an oxidized form. The electrical potential of the cell **10** is depleted once the fuel at the fuel electrode **12** is entirely oxidized or oxidation is arrested due to passivation of the fuel electrode. A portion of the switching system **60** may be positioned in between the oxidant electrode **14** and the load L so that the oxidant electrode **14** may be connected and disconnected from the load L, as desired. Again, more details about the switching system **60**, and the electrical configuration thereof, is provided below.

To limit or suppress hydrogen evolution at the fuel electrode **12** during discharge mode and during quiescent (open circuit) periods of time, salts may be added to retard such a reaction. Salts of stannous, lead, copper, mercury, indium, bismuth, or any other material having a high hydrogen overpotential may be used. In addition, salts of tartrate, phosphate, citrate, succinate, ammonium or other hydrogen evolution suppressing additives may be added. In an embodiment, metal fuel alloys, such as Al/Mg may be used to suppress hydrogen evolution. Other additives may also or alternatively be added to the ionically conductive medium, including, but not limited to additives which enhance the electrodeposition process of the metal fuel on the fuel electrode **12**, such as is described in U.S. Provisional Patent Application 61/304,928, now converted into U.S. patent application Ser. No. 13/028,496, incorporated in its entirety herein by reference. After the fuel in the cell **10** has been entirely oxidized, or whenever it is desirable to regenerate the fuel within the cell **10** by reducing oxidized fuel ions back to fuel, the fuel electrode **12** and the oxidant electrode **14** may be decoupled from the external load L and coupled to a power supply PS. As noted above, such connections may be made, for example, with the use of the switching system **60** and the terminal selector system **62**.

The power supply PS is configured to charge the cell **10** by applying a potential difference between the fuel electrode **12** and the oxidant electrode **14** such that the reducible species of the fuel is reduced and electrodeposited onto at least one of the permeable electrode bodies **12***a*-**12***d* and the corresponding oxidation reaction takes place at the oxidant electrode **14**, which is typically oxidation of an oxidizable species to evolve oxygen, which may be off-gassed from the cell **10**. In an embodiment wherein oxygen is the oxidant, oxygen ions in an aqueous electrolytic solution are oxidized. The oxygen ions may be available from an oxide of the fuel (e.g., ZnO when zinc is the fuel), hydroxide ions (OH^-), or water molecules (H_2O). As described in detail in U.S. patent application Ser. No. 12/385,489, which has been incorporated herein by reference, in an embodiment only one of the permeable electrode bodies, such as **12***a*, is connected to the power supply PS so that the fuel reduces onto the permeable electrode body and progressively grows to and on the other permeable electrode bodies **12***b*-**12***d*, one by one. The switching system **60** may control how the permeable electrode bodies **12***a*-**12***d* and the oxidant electrode **14** participate in the electrochemical reactions of the cell, as is described in greater detail below.

FIG. **8** shows an embodiment where a separate charging electrode **70** of cell **10** in electrochemical cell system **100** is provided to function as the charging electrode, rather than the oxidant electrode **14**. Again, in some embodiments other cells **10** may be part of electrochemical cell system **100**, as shown. As illustrated in FIG. **2**, the separate charging electrode **70** may be positioned between the fuel electrode **12** and the oxidant electrode **14**, with a spacer **72** and the seal member **17** being positioned between the separate charging electrode **70** and the oxidant electrode **14**. The spacer **72** is non-conductive and has openings through which the ionically conductive medium may flow.

In the embodiment described above with respect to FIG. **7**, the oxidant electrode **14** functions as the cathode during power generation/discharge, and as the anode during charging, as described above. In FIG. **8**, the oxidant electrode **14** remains the cathode during power generation/discharge, but may be disconnected during charging, while the separate charging electrode **70** is connected to the power supply PS to function as the anode. During current generation, the fuel on the fuel electrode **12** is oxidized, generating electrons that are conducted to power the load L and then conducted to the oxidant electrode **14** for reduction of the oxidizer (as discussed in more detail above). In embodiments comprising the separate charging electrode **70**, the switching system **60** may control how the permeable electrode bodies **12***a*-**12***d* the oxidant electrode **14**, and the separate charging electrode **70** participate in the electrochemical reactions of the cell, as is described in greater detail below.

It is also possible in any of the embodiments of the invention to apply the cathodic potential to any or all of the electrode bodies **12***a*-**12***d* of the fuel electrode **12**, rather than to just one to produce body-by-body progressive growth. Progressive growth emanating from one terminal is advantageous because it provides more density of the electrodeposited fuel. Specifically, the growth in the previously connected electrode bodies continues as each subsequent body is connected by the progressing growth. This and other advantages are discussed in greater detail in U.S. patent application Ser. No. 12/385,489, which has been incorporated herein by reference. With all the electrode bodies subject to the same potential, the growth will only occur until a short occurs between the charging electrode, which is the oxidant electrode **14** in the embodiment of FIG. **7** and the separate charging electrode **70** in the embodiment of FIG. **8**, and the electrode body proximate to it. Thus, it is possible to have a faster, but less dense, growth in this manner, which may be amenable to certain re-charging needs.

The embodiments illustrated in FIGS. **7** and **8** should not be considered to be limiting in any way and are provided as non-limiting examples of how the cell **10** may be configured to be rechargeable. The recharge mode of the present invention, in the context of the switching system **60**, is discussed in greater detail below. As another example, U.S. patent application Ser. No. 12/885,268 (published as U.S. Patent Application Publication No. 2011/0070506), filed on Sep. 17, 2010, the entire content of each of which is incorporated herein by reference, describes embodiments of a rechargeable electrochemical cell system with charge/discharge mode switching in the cells.

Returning to FIG. **4**, after the ionically conductive medium has passed through the fuel electrode **12**, the medium may flow into the outlet channel **26** that is connected to the outlets **36** of the cavity **18** of the electrode holder **16** and the outlet **22**. The outlet **22** may be connected to the inlet **20** in embodiments where the medium is recirculated in the cell **10**, or to an inlet of an adjacent cell, as discussed in further detail below, when a plurality of cells **10** are fluidly connected in series. In an embodiment, the outlet **22** may be connected to a vessel to collect the medium that has been used in the cell **10**. Again, in various embodiments the flow of the ionically conductive medium may vary, for example by flowing through a plurality of cells **10** in series or parallel, at a constant rate or a varying rate, continuously or intermittently.

The cells **10** illustrated in FIGS. **1** and **2** may be fluidly connected in series. Details of embodiments of cells that are connected in series are provided in U.S. patent application Ser. No. 12/631,484 (published as U.S. Patent Application Publication No. 2010/0316935), filed Dec. 4, 2009 and incorporated herein by reference in its entirety. The outlet **22** of a first cell **10** may be fluidly connected to the inlet **20** of a second cell **10**, and the outlet **22** of the second cell **10** may be connected to the inlet **20** of a third cell, and so on. Although the embodiment of FIGS. **1** and **2** illustrates two cells **10**, additional cells may be stacked and fluidly connected to the illustrated cells. Due to the meandering, tortuous paths that are created by the inlet channel **24** and the outlet channel **26**, described above and illustrated in FIGS. **3** and **4**, the length of the flow passageways for the medium via the channels **24**, **26** is greater than the distance between the fuel electrode **12** and the oxidant electrode **14** in each of the cells **10**. This creates an ionic resistance between the pair of fluidly connected cells that is greater than an ionic resistance within an individual cell **10**. This may reduce or minimize internal ionic resistance loss of the stack of cells **100**, as discussed in U.S. patent application Ser. No. 12/631,484.

In an embodiment of operation, the fuel electrode **12**, which already has metal fuel deposited thereon, is connected to the load L and the oxidant electrode **14** is connected to the load L. The ionically conductive medium enters the inlet **20** under positive pressure and flows through the inlet channel **24**, the inlets **34** of the cavity **18**, and into the flow lanes **42**. The ionically conductive medium flows across the permeable electrode bodies **12***a*-**12***d* in the flow lanes **42** defined by the elongated middle portions **22** of the spacers **40**. The ionically conductive medium may also permeate through the permeable electrode bodies **12***a*-**12***d* of the fuel electrode **12**. The ionically conductive medium simultaneously contacts the fuel electrode **12** and the oxidant electrode **14**, thereby allowing the fuel to oxidize and conduct electrons to the load L, while the oxidizer is reduced at the oxidant electrode **14** via the electrons that are conducted to the oxidant electrode **14** by the load L. After the ionically conductive medium has passed through the flow lanes **42**, the medium flows out of the cavity **18** via the outlets **36** of the cavity **18**, through the outlet channel **24**, and out the outlet **22** of the cell **10**.

When the potential of the cell **10** has been depleted or when it is otherwise desirable to recharge the cell **10**, the fuel electrode **12** is connected to the negative terminal of the power supply PS and the charging electrode, which may be the oxidant electrode **14** or the separate charging electrode **70**, is connected to the positive terminal of the power supply PS. Such connections may again be through the switching system **60**, discussed below. In the charging or recharge mode, a cathode portion of the fuel electrode **12** becomes the cathode and an anode portion of the fuel electrode **12** and/or the charging electrode **14**, **70** becomes the anode, as is described in greater detail below. By providing electrons to a cathode portion of the fuel electrode **12**, fuel ions may reduce into fuel and redeposit onto the permeable electrode bodies **12***a*-**12***d*, as is described in greater detail below, while the ionically conductive medium circulates through the cell **10** in the same manner as described above with respect to the discharge mode.

The flow lanes **42** provide directionality and distribution of the ionically conductive medium across the fuel electrode **12**. The flow lanes **42** may also prevent the particulates from settling and/or covering the electrodes. When the cell **10** is in charging mode, the improved distribution of the particulates across the fuel electrode **12** allows for a more uniform deposition of the reduced fuel onto the fuel electrode **12**, which improves the density of the fuel on the fuel electrode **12**, and increases the capacity and energy density of the cell **10**, thereby enhancing the cycle-life of the cell **10**. In addition, by having the ability to control the distribution of the precipitates or reaction by-product during discharge, early passivation/deposition of the by-product on the fuel electrode **12** may be prevented. Passivation leads to lower fuel utilization and lower cycle life, which is undesirable.

The examples of FIGS. **1**-**8** are not limiting, and are provided solely for context to understand general principles of an embodiment of the cells **10** of the cell system **100**. Any cell construction or configuration may be used. With an understanding of the cell system provided, attention is turned to the configuration and operation of the switching system **60** of the invention.

As noted, during a charging mode for the cell **10**, a potential difference is applied across electrodes in the cell **10**. Although either the oxidant electrode **14** or the separate charging electrode **70** generally function as the anode during charging, an anodic potential may be applied to other electrodes, such as some of the electrode bodies in the fuel electrode **12**. Likewise, during charging a cathodic potential may be initially applied to electrode body **12***a* of the fuel electrode **12**, but may also be initially applied to one or more of the other permeable electrode bodies **12***b*-**12***d* of the fuel electrode **12**. As such, those permeable electrode bodies **12***a*-**12***d* of fuel electrode **12** having a cathodic potential behave as a cathode during charge, and serve as a reduction site for a reducible fuel species, such as the oxidized fuel ions created in the cell during discharging.

As the reducible fuel species is reduced on those of permeable electrode bodies **12***a*-**12***d* having the cathodic potential, the oxidant electrode **14** or the separate charging electrode **70** and/or those of the permeable electrode bodies **12***b*-**12***d* having the anodic potential will oxidize an oxidizable oxygen species, such as the reduced oxidant species created in the cell during discharging. Thus, when the cell **10** is a metal-air cell, the reducible metal fuel species is being reduced and electrodeposited on some of the permeable electrode bodies **12***a*-**12***d* of the fuel electrode **12**, and the oxidizable oxygen species is being oxidized to oxygen gas, which may be off-gassed from the cell **10**. In this embodiment, those electrodes and electrode bodies having an anodic potential may be considered an oxygen evolving electrode (OEE).

To determine which of the electrodes (i.e. permeable electrode bodies **12***a-d*, the oxidant electrode **14** and/or the separate charging electrode **70**) have anodic potentials or cathodic potentials during charging, electrical connections therebetween may be controlled by the switching system **60**, as is discussed in greater detail below.

It may be advantageous to the fuel growth for the potential difference used to charge the cell **10** to be applied between adjacent bodies in the cell **10**, such that an electrode body having the anodic potential is adjacent to an electrode body having the cathodic potential. Once sufficient fuel growth has occurred on the electrode body having the cathodic potential, the electrode having the anodic potential may change, so that the permeable electrode body that previously was part of a set of electrode bodies having an anodic potential may become part of a set of electrode bodies having the cathodic potential. In an embodiment wherein there are N permeable electrode bodies, the application of the anodic potential from the power source to permeable electrode bodies **2** to N and the charging electrode may comprise connecting all of the electrode bodies plus the charging electrode together at the same time, then disconnecting each of electrode bodies **2** to N in order. Alternatively, in an embodiment, the application of the anodic potential from the power source to permeable electrode bodies **2** to N and the charging electrode could comprise connecting and disconnecting each of the electrode bodies and the charging electrode individually in order (such that electrode body **2** is connecting to the anodic potential, then is disconnected and electrode **3** is connected to the anodic potential, and so on until the charging electrode is finally connected to complete the growth).

In an embodiment, the charging electrode may merely be the last electrode to receive the anodic potential during charging. For example, the charging electrode could be the oxidant electrode or a separate electrode. When the charging electrode is a separate electrode, it could have a specialized construction different from the electrode bodies of the fuel electrode, or could be the same as the permeable electrode bodies (i.e. just one more electrode body), but for the fact that growth of the fuel during charging does not continue past it.

In the above-described embodiment illustrated in FIGS. **1**-**2**, the progressive changing of which electrode(s) have the anodic potential may follow the fuel growth through each of the permeable electrode bodies **12***a*-**12***d*, so that an electrode having an anodic potential remains the electrode body spaced adjacent to an electrode having the cathodic potential. As shown in the embodiments of the following Figures, the switch system **60** may be configured to selectively connect and disconnect the various electrodes and electrode bodies to maintain the adjacent positions of the anodic potential and the cathodic potential.

FIGS. **9**-**12** show embodiments of the switching system **60** of the cell **10**. The cell **10** is connectable to the power supply PS, the load L, or to other cells **10** in series, through a first terminal **130** and a second terminal **140**, wherein the first terminal **130** is negative (cathodic) during recharging, and the second terminal **140** is positive (anodic) during recharging. As shown, the cell **10** has a fuel electrode **12** comprising permeable electrode bodies **12***a*-**12***d*, a charging electrode **70**, and an oxidant electrode **14**. In an embodiment, the plurality of switches may selectively couple at least some of the permeable electrode bodies **12***b*-**12***d* to a power source, such as power supply PS, for application of an anodic potential during a recharging mode of the cell **10**, in which a cathodic potential is applied to at least electrode body **12***a*, as will be described in greater detail below.

In FIG. **9**, the switching system **60** includes a bypass switch **150**, configured to provide a direct connection between the first terminal **130** and the second terminal **140**. The bypass switch **150** may be similar to that described in U.S. patent application Ser. No. 12/885,268, which has been incorporated herein in its entirety by reference. A cell **10** can be bypassed with bypass switch **150** for a number of reasons that affect the performance of the stack.

For example, a short between charging electrode **70** and the electrode bodies **12***a*-**12***d* having a cathodic potential during charge (detected by voltage measurement as described below) may lead to expense of parasitic power during charge.

An electrical short may lead to a sudden drop in voltage between the charging and fuel electrodes as the current is shunted between the charging and fuel electrodes. Another example is during discharge, where any cell **10** that has a higher kinetic or ohmic loss affects the round trip efficiency and discharge power of the stack. Also, consumption of fuel in the cell **10** during discharge earlier than other cells **10** can lead to voltage reversal in the cell **10** and stack power loss, and can be prevented by bypassing the cell **10** when the discharge voltage falls below a critical value. Complete consumption of zinc or other fuel during discharge leads to a sudden drop in voltage between the fuel and oxidant electrodes. Any other criteria to detect the performance of cells **10** may be used, and the examples herein are not limiting. Certain cells **10** may not meet performance requirements (for example, maximum power during discharge) due to yield issues and problems related to fabrication and assembly of electrodes. These cells **10** can be permanently placed in bypass mode. Other cells **10** may meet performance requirements initially, however may have cycle life issues and can be placed in bypass mode after the performance falls below a required limit. Thus, bypassing a cell **10** through bypass switch **150** provides an option to increase reliability and performance of the stack.

The switching system **60** of FIG. **9** also includes an oxidant electrode switch **160** associated with the oxidant electrode **14**. The oxidant electrode switch **160** would be closed during discharge, so that an electric potential across the fuel electrode **12** and the oxidant electrode **14** may allow a current to be drawn by a load L connected between the first terminal **130** and the second terminal **140**, which during discharge would have positive and negative polarities respectively.

A charging electrode switch **170** may be associated with the charging electrode **70**, such that the charging electrode **70** may be electrically connected to the second terminal **140** when the power supply PS is connected between the first terminal **130** and the second terminal **140**. As discussed below, the charging electrode **70** may not always have an anodic potential applied to it, and in an embodiment may only have an anodic potential when fuel growth between it and electrode body **12***d* is desired. Also shown are switches **180**, **190**, and **200**, associated with electrode bodies **12***b*-**12***d* respectively, all of which are configured to connect electrode bodies **12***b*-**12***d* to the second terminal **140** as well.

As was noted, it is advantageous that an electrode having an anodic potential be adjacent to an electrode having a cathodic potential, so that growth on the electrode having the cathodic potential is enhanced. Such enhancement may, for example, include greater density of fuel growth than if the electrode having the anodic potential is further from the closest electrode having the cathodic potential (i.e. if a neutral electrode separates the electrodes having the anodic and cathodic potentials). This enhanced density may be due to the initial dendrites that first contact the anodic body being disrupted because they lack sufficient cross-section to carry the current between the anodic and cathodic bodies. That is, they burn off similarly to a fuse element subject to excess current. This delays shorting between the anodic and cathodic bodies, which takes place when the density has increased further to provide dendrites of sufficient cross-sectional area (individually and/or collectively) to enable the current conduction without disruption. Another advantage may be lower electrolyte IR loss in configurations where the distance between the charging electrode **70** and the fuel electrode **12** is lower, as compared to configurations wherein the electrode having the anodic potential is further from the closest electrode having the cathodic potential (i.e. where neutral electrodes separate the electrodes having the anodic and cathodic potentials). This IR efficiency advantage resulting from less distance between anodic and cathodic electrodes may be realized both in embodiments where metallic growth is occurring between the electrodes and in other embodiments, such as a metal hydride fuel where the hydrogen ions are being reduced.

To achieve progressive modification of which electrodes have the anodic potential, to account for shifts between electrodes having an anodic potential versus electrodes having a cathodic potential, the cell **10** in the charging mode would be configured such that the bypass switch **150** is open, so that current does not bypass the cell **10**. Because the cell is in a charging mode, the oxidant electrode switch **160** is also open, so that the oxidant electrode **14** is electrically disconnected from the cell **10**. Since initially fuel growth is desired on electrode body **12***a*, only electrode body **12***a* is electrically connected to first terminal **130**, applying the cathodic potential thereto. To establish an anodic potential on the electrode body adjacent to electrode body **12***a*, at least electrode body **12***b* will be electrically connected to second terminal **140**. To achieve this electrical connection in the illustrated embodiment, at least switch **180** is closed. In an embodiment, electrode bodies **12***c*-**12***d*, and charging electrode **70** may also be electrically connected to second terminal **140**, and thus may also have the anodic potential. Because of the potential difference between the electrode(s) having the anodic potential (i.e. initially electrode body **12***a*) and the electrode(s) having the cathodic potential (i.e. initially at least electrode body **12***b*), reducible fuel species in the ionically conductive medium may be reduced at the electrode having the initial cathodic potential (electrode body **12***a*) while cations in the ionically conductive medium are oxidized at electrode body **12***b* (and any other body/electrode to which the anodic potential is applied).

Once fuel growth on the electrodes having the cathodic potential progresses to a certain point, for example, to the point where an electrical connection is formed between the electrode(s) having the cathodic potential and the electrode(s) having the anodic potential, the switching system **60** may disconnect the shorting electrode body that had the anodic potential, such that that electrode body has a cathodic potential applied to it, and a potential difference may be formed again between adjacent electrode bodies. This may require the further electrical connection of the adjacent electrode body to the second terminal **140**, if the electrical connection did not already exist, so as to create the anodic potential on that body. For example, in FIG. **9**, once fuel growth on electrode body **12***a* causes a short with electrode body **12***b*, switch **180** is opened so that both electrode body **12***a* and, through the electric connection of the fuel growth, electrode body **12***b*, have the cathodic potential. On the other hand, switch **190** closes (if it was not already closed before), such that at least electrode body **12***c* has an anodic potential, thus maintaining the adjacent electrode body separation for the potential difference between the electrode(s) having the cathodic potential and the electrode(s) having the anodic potential.

The progressive shifting of which electrodes have the cathodic potential and which electrodes have the anodic potential may continue throughout the cell **10**, with the opening of switches **190** and **200**, until no further progression is desired or possible. For example, in the illustrated embodiment, wherein there is a separate charging electrode **70**, the progression will end when the separate charging electrode **70** is the only electrode body having the anodic potential, and all permeable electrode bodies **12***a*-**12***d* of the fuel electrode **12** have the cathodic potential. Charging of the cell **10** may subsequently end when fuel growth on electrode body **12***d* causes an electrical connection between electrode body **12***d* and charging electrode **70**. In an embodiment, the switching system **70** may be configured to have an over-charge configuration, wherein the cell may be configured to selectively apply a cathodic potential to charging electrode **70** by opening switch **170**, and closing switch **160**, applying the anodic potential to the oxidant electrode **14**, utilizing it for further charging of cell **10** by permitting fuel growth on the charging electrode **70**.

Charging of the cell **10** may in various embodiments progress from electrode body to electrode body among the plurality of permeable electrode bodies **12***a*-**12***d*, or may end based on criteria such as the voltage, current, slope of voltage, slope of current, charge capacity, or value of impedance or resistance. Such measurements in various embodiments may be taken over one or more of the electrode bodies **12***a*-**12***d*, or across one or more cells **10**. In an embodiment, charging may end based on a sensing electrode placed between the charging electrode and the last permeable electrode body **12***d* of the fuel electrode **12**.

During discharge of the cell **10** in the embodiment of FIG. **9**, oxidant electrode switch **160** would be closed, while charging electrode switch **170** would be open. Additionally, switches **180**, **190**, and **200** would be open, and fuel consumption would be from electrode body **12***d* to electrode body **12***a*, wherein the electrical connection between the electrode bodies **12***a*-**12***d* are through the fuel growth. In the illustrated embodiment, this is so electrode bodies **12***a*-**12***d* are not shorted to the oxidant electrode **14** by oxidant electrode switch **160**.

Continuing to FIG. **10**, another embodiment of switching system **60** is illustrated for the cell **10**. Again there is the bypass switch **150**, configured to connect first terminal **130** directly to second terminal **140**, bypassing the cell **10**. The switching system **60** also includes a series of connecting switches **210***a-d*, configured to selectively and progressively connect each of the electrode bodies **12***b-d* to either the first terminal **130** or the second terminal **140**, such that each of the electrode bodies **12***b-d* either has a cathodic potential (i.e. is connected to at least electrode body **12***a*) or an anodic potential (i.e. is connected to at least charging electrode **70**). As shown, during charging, bypass switch **150** would be open so the cell is not bypassed. Oxidant electrode switch **160** would also be open, so that oxidant electrode **14** is disconnected during the charging process. Charging electrode switch **170** would be closed so that at least charging electrode **70** would have an anodic potential. To promote minimal distance between the electrode(s) having the cathodic potential (initially just electrode body **12***a*) and the electrodes having the anodic potential, switches **210***b*, **201***c*, and **210***d* would be closed, so that the anodic potential created through the electrical connection to second terminal **140** is applied through electrode bodies **12***b*-**12***d*, as well as charging electrode **70**. As fuel growth on electrode body **12***a* progresses, it will eventually contact electrode body **12***b*. In an embodiment, at that time switch **210***b* would open, so that electrode bodies **12***a*-**12***b* have the cathodic potential, while electrode bodies **12***c*-**12***d* and charging electrode **70** have the anodic potential. In an embodiment, switch **210***a* would also be closed, so that a stronger electrical connection between electrode bodies **12***a*-**12***b* is formed, beyond the electrical connection of the fuel growth. Such progression could continue, as above, with the opening of switches **210***c* and **210***d* respectively, as the number of electrode bodies having the anodic potential shrinks, while the number of electrodes having the cathodic potential grows. Again, in some embodiments switches **210***b* and **210***c* could close in progression, to form a stronger electrical connection between electrode bodies **12***a*-**12***d* as the number of electrodes having a cathodic potential progressively grows.

During discharge of the cell **10** in the embodiment of FIG. **10**, oxidant electrode switch **160** would be closed, while charging electrode switch **170** would be open. In an embodiment switches **210***a*-**210***d* could remain open and fuel consumption would be from electrode body **12***d* to electrode body **12***a*, wherein the electrical connection between the electrode bodies **12***a*-**12***d* are through the fuel growth. In another embodiment, switches **210***a*-**210***d* could be closed, so that an electrical connection is between all electrode bodies **12***a*-**12***d* of the fuel electrode **12**, and fuel is oxidized throughout the fuel electrode **12** while an oxidant is reduced at the oxidant electrode **14**. This is permissible in this embodiment because opening switch **170** also prevents the electrode bodies **12***a-d* from being shorted to the oxidant electrode **14** by oxidant electrode switch **160**.

Another embodiment of the switching system **60** for the cell **10** is seen in FIG. **11**. Once more, the switching system **60** comprises the bypass switch **150**, configured to selectively connect the first terminal **130** directly to the second terminal **140**, in order to bypass the cell **10**. The switching system **60** of the embodiment of FIG. **11** also includes another series of connecting switches **220***a-d*, configured to selectively connect each of the electrode bodies **12***a-d* to the charging electrode **70**. Again, the switching system **60** may be configured to allow progressive change of those electrodes having the cathodic potential (i.e. at least electrode body **12***a*) and those electrodes having the anodic potential (i.e. at least charging electrode **70**). As shown, during charging, bypass switch **150** would be open so the cell is not bypassed. Oxidant electrode switch **160** would also be open, so that oxidant electrode **14** is disconnected during the charging process. Charging electrode switch **170** would be closed so that at least charging electrode **70** would have an anodic potential. Switch **220***a* would be opened so that the cell is not bypassed from first terminal **130** to second terminal **140** through switch **220***a* and switch **170**. To promote minimal distance between the electrode(s) having the cathodic potential (initially just electrode body **12***a*) and the electrodes having the anodic potential, at least switch **220***b* would be closed, so that at least electrode bodies **12***b*, as well as charging electrode **70**, have the anodic potential. As fuel growth on electrode body **12***a* progresses, it will eventually contact electrode body **12***b*. In an embodiment, at that time switch **220***b* would open, so that electrode bodies **12***a*-**12***b* have a cathodic potential (connected through the fuel growth). Switch **220***c* would then close, if it was not closed before, so that at least electrode body **12***c*, as well as charging electrode **70**, would have the anodic potential. Such progression could continue, as above, with the opening of switches **210***c* and **210***d* respectively, as the number of electrode bodies having the anodic potential shrinks, while the number of electrode bodies having the cathodic potential grow.

During discharge of the cell **10** in the embodiment of FIG. **11**, oxidant electrode switch **160** would be closed, while charging electrode switch **170** would be open. In an embodiment switches **220***a*-**220***d* could remain open and fuel consumption would be from electrode body **12***d* to electrode body **12***a*, wherein the electrical connection between the electrode bodies **12***a*-**12***d* are through the fuel growth therebetween.

The progressive shifting of which electrode bodies have a cathodic potential versus which electrode bodies have an anodic potential may be analogized as the cell **10** having N electrode bodies defining two conceptual electrodes, a cathodic potential electrode and an anodic potential electrode. In the cell, the constituent makeup of the cathodic potential electrode may begin with a single electrode body, while the anodic potential electrode may comprise at least the adjacent electrode body, up to all other electrode bodies. During charging, fuel grows on the cathodic potential electrode until, for example, no further growth on the electrode body is possible (i.e. the cathodic potential electrode has shorted to the anodic potential electrode). At that time, the electrode body of the anodic potential electrode that is adjacent to the cathodic potential electrode is reassigned to become part of the cathodic potential electrode, through an electrical connection formed by the fuel growth and/or through the use of electrical circuitry or switches associated with the electrode bodies of the cell. With the reassignment, the cathodic potential electrode now comprises two electrode bodies, while the anodic potential electrode has one less than its initial number of electrode bodies. As a potential difference may resume between the cathodic potential electrode and the anodic potential electrode, fuel growth from charging may resume, again until, for example, no further growth on the electrode bodies of the cathodic potential electrode is possible.

The progressive shifting of the constituent makeup of the cathodic potential electrode and the anodic potential electrode may continue throughout the cell, for example with the opening and/or closing of switches associated with the electrode bodies, until no further progression is desired or is possible. For example, once the anodic potential electrode comprises only a single electrode body, no further progression is possible. The charging of the cell may subsequently end when fuel growth on the cell causes an electrical connection to form between the conceptual cathodic potential electrode and the conceptual anodic potential electrode that comprises only a single electrode body.

Again, in various embodiments charging of the cell **10** may progress from electrode body to electrode body among the plurality of permeable electrode bodies **12***a*-**12***d*, or may end based on criteria such as the voltage, current, slope of voltage, slope of current, charge capacity, or value of impedance or resistance. Such measurements in various embodiments may be taken over one or more of the electrode bodies **12***a*-**12***d*, or across one or more cells **10**. In an embodiment, charging may end based on a sensing electrode placed between the charging electrode and the last permeable electrode body **12***d* of the fuel electrode **12**.

As noted previously, in an embodiment, multiple electrochemical cells **10** may be combined in cell system **100**. Shown in FIGS. **12**A-C are electrochemical cell systems **100** of the embodiments of FIGS. **9**-**11**, however comprising N electrochemical cells **10**. The number N is any integer greater than or equal to two, and is not limited to any particular number. As illustrated, the bypass switches **150** in the switching systems **60** of each cell **10** are configured to selectively bypass each cell **10** by providing a direct connection between the first terminal **130** and the second terminal **140**. Such a connection may again be used to bypass defective cells **10**, or for any other reason. Also, in various embodiments of cell systems **100**, different embodiments of the switching system **60** (such as those found in FIGS. **9**-**11**) may be used in conjunction with one another in a single cell system **100**.

In any embodiment, the switches of the switching system **60** (or any other switch described herein) may be of any type, and the term switch is broadly intended to describe any device capable of switching between the modes or states described. For example, in some non-limiting embodiments, the switches may be single pole single throw or single pole double throw. They may be of the pivoting, sliding or latching relay type. Also, semiconductor based switches may be used as well. The switches may be activated electrically (electromechanical relay) or magnetically or by other methods known to those familiar in the art. Any other suitable type of switch may be used, and the examples herein are not limiting. In an embodiment, the plurality of switches may be connected in series if the switch has a leakage current in one direction. For example, the body diode of a MOSFET semiconductor based switch will conduct in one direction and the leakage current can be eliminated by placing MOSFET semiconductor based switches facing back to back in series.

Any suitable control mechanism may be provided to control the action of switches in the switching system **60** and/or the terminal selector system **62**. As shown in FIG. **13**, in an embodiment the switches of the switching system **60** may be controlled by a controller **230**. The controller **230** may be of any construction and configuration. In an embodiment, the controller **230** may be configured to manage application of the anodic potential from the power supply PS to permeable electrode bodies **12***b-d* and the charging electrode **70**. The controller **230** may cause electrodeposition of metal fuel, through reduction of reducible ions of the metal fuel from the ionically conductive medium, to progressively grow from permeable electrode body **12***a* to each subsequent electrode body **12***b-d* for application of a cathodic potential to each subsequently connected electrode body **12***b-d*. The controller **230** may also cause removal of the anodic potential from each subsequently connected electrode body, and may cause application of the anodic potential to at least the subsequent electrode body unconnected by the electrodeposition, or the charging electrode where the last electrode body (i.e. electrode body **12***d*) has been electrically connected by the electrodeposition to the prior electrode bodies **12***a-c*. Such application of the anodic potential may be configured to permit or cause oxidization of an oxidizable species of the oxidant.

In an embodiment, the controller **230** may comprise hard-wired circuitry **232** that manipulates the switches based on an input **234** determining the proper switch configuration. The controller **230** may also include a microprocessor for executing more complex decisions, as an option. In some embodiments, the controller **230** may also function to manage connectivity between the load L and the power source and the first and Nth cells (i.e. may control the terminal selector system **62** described above). In some embodiments, the controller **230** may include appropriate logic or circuitry for actuating the appropriate bypass switches **150** in response to detecting a voltage reaching a predetermined threshold (such as drop below a predetermined threshold). In some embodiments, the controller **230** may further comprise or be associated with a sensing device **236**, including but not limited to a voltmeter (digital or analog) or potentiometer or other voltage measuring device or devices, that can be used to determine when to modify the configuration of the plurality of switches, such as to maintain the proximity of the anode and the cathode as fuel growth progresses during charging. In some embodiments, the sensing device **236** may instead measure current, resistance, or any other electrical or physical property across or of the cell **10** that may be used to determine when to modify the configuration of the plurality of switches. For example, the sensing device **236** may measure a spike in current or a drop in potential difference between two electrode bodies. In some embodiments, the controller **230** may control the switches of the switching system **60** based on the passage of increments of time. For example, in an embodiment the time for fuel growth to progress between adjacent electrode bodies may be known, and used to calculate when to operate the switching system **60** so as to progressively rewire the electrodes to maintain an adjacent separation between the anode and the cathode. In an embodiment, the controller **230** may control the switches of switching system **60** to provide a high efficiency mode for the cell, such as is disclosed in U.S. Provisional Patent Application 61/323,384, now pending as U.S. patent application Ser. No. 13/083,929, each of which is incorporated in its entirety herein by reference.

In some embodiments, the controller **230** may be configured to selectively enter different charging modes. For example, in one mode a plurality of electrode bodies may initially have an anodic potential, but the number decreases as the electrode bodies are given a cathodic potential. In another mode, only a single electrode body has an anodic potential at any given time, and the electrode body with the anodic potential changes as prior electrode bodies are given the cathodic potential. For example, in the former mode, the controller **230** may close all switches associated with the charging electrode **70** and electrode bodies **12***b-d* during recharge, such that an anodic potential is applied to each of electrode bodies **12***b-d* and the charging electrode **70**. The controller **230** may then progressively open the switches associated with each of electrode bodies **12***b-d* as the electrode bodies **12***b-d* progressively become electrically connected to electrode body **12***a*, and thus have a cathodic potential. In the latter mode, the controller may initially close only the switch associated with electrode body **12***b*, giving electrode body **12***b* an anodic potential while electrode body **12***a* has a cathodic potential. When fuel growth on electrode body **12***a* reaches electrode body **12***b*, creating an electrical connection therebetween, the controller **230** may open the switch associated with electrode body **12***b* that gave electrode body **12***b* the anodic potential, such that electrode body has a cathodic potential through its electrical connection to electrode body **12***a*. The controller **230** may then proceed to close the switch associated with electrode body **12***c*, to provide electrode body **12***c* with the anodic potential, again creating a potential difference, and the progression of fuel growth. These progressions of switch reassignments by the controller **230** may continue through or until only the charging electrode **70** has the anodic potential, as is described above.

As seen in FIG. **14**, another aspect of the present invention may include a method **240** for charging the electrochemical cell **10**. Again, electrochemical cell **10** comprises the fuel electrode **12** comprising the plurality of permeable electrode bodies **12***a-d*. Although four permeable electrode bodies are listed, any number greater than or equal to two are possible. The cell **10** further includes the oxidant electrode **14**, and the charging electrode, which may be the oxidant electrode **14** or the separate charging electrode **70**. The cell **10** additionally includes the ionically conductive medium, and the switching system **60** comprising a plurality of switches, wherein at least some of the plurality of switches are associated with one of the permeable electrode bodies **12***a-d*, the oxidant electrode **14**, and the charging electrode (i.e. oxidant electrode **14** or separate charging electrode **70**). During a charging mode, reducible fuel ions in the ionically conductive medium are reduced and electrodeposited as fuel in oxidizable form on a cathode comprising at least permeable electrode body **12***a* while an oxidant is oxidized on an anode comprising at least an adjacent one of the permeable electrode bodies **12***b-d* and/or the charging electrode (i.e. charging electrode **70**).

The method **240** starts at **250**, and includes at **260** electrically connecting the cathode (i.e. in an embodiment, initially just permeable electrode body **12***a*), distal from the charging electrode, to the negative terminal of power supply PS, and the anode (i.e. initially at least permeable electrode body **12***b*) to the positive terminal of the power supply PS, creating a potential difference therebetween. The method **240** continues at **270**, wherein, the fuel is electrodeposited on the cathode (i.e. at least permeable electrode body **12***a*). As seen in step **280**, the method **240** may continue by determining if fuel growth has progressed to beyond a threshold amount. In an embodiment the threshold amount may be ascertained when the cell **10** is shorted by the fuel growth creating an electrical connection through the fuel growth between the cathode (i.e. permeable electrode body **12***a*) and the anode (i.e. permeable electrode body **12***b*). As shown, if fuel growth has not reached the threshold amount, the growth of fuel at **270** is repeated. Once the threshold amount is reached, the method continues at **290**, wherein it may be determined if further fuel growth is both possible and desired. In an embodiment, the determination at **290** may include ascertaining if there are additional electrode bodies, such as permeable electrode bodies **12***c-d*, that fuel growth may be possible on. If so, the method continues at **300** by using the plurality of switches of the switching system **60** to disconnect the connecting electrode body (i.e. permeable electrode body **12***b*) from the anode, and if it were not connected through the switching system **60** before, connecting the next adjacent electrode body (i.e. permeable electrode body **12***c*) to the anode. This creates the potential difference between the cathode (now comprising permeable electrode bodies **12***a-b*) and the anode (comprising at least permeable electrode body **12***c*). The method **240** then returns to **270** wherein fuel growth continues on the cathode. If no further fuel growth is possible or desired at **290**, the method **240** continues to **310** by disconnecting at least the negative terminal of the power source PS from the cell **10** to discontinue the charging process. The method **240** may then end at **320**.

Shown in FIG. **15**, another aspect of the present invention may include a method **330** for discharging the electrochemical cell **10**, which may be similar to that described above as related to FIG. **14**. During the discharge mode, fuel on permeable electrode bodies **12***a*-**12***d* is oxidized (and thus is consumed into the ionically conductive medium as reducible fuel ions), while an oxidizer is reduced at the oxidant electrode **14**.

The method **330** starts at **340**, and includes at **350** using the plurality of switches of the switching system **60** to connect the permeable electrode bodies **12***a-d* that contain fuel. In an embodiment, if the cell **10** is completely charged all permeable electrode bodies **12***a-d* would be electrically connected to one another. As the cell **10** is in discharge mode, the plurality of switches of the switching system **60** would be configured to electrically disconnect the separate charging electrode **70** (if present). In an embodiment, the method **330** would continue at **360** by electrically connecting the cathode (i.e. the air cathode, oxidant electrode **14**) to the negative terminal of load L, and the anode (i.e. the fuel electrode **12**, containing the electrically connected permeable electrode bodies **12***a-d*) to the positive terminal of the power supply PS, creating a potential difference therebetween. The method **330** continues at **370**, wherein the fuel is consumed on the fuel electrode **12**. In an embodiment, because the plurality of switches **60** connect the permeable electrode bodies **12***a-d*, an anodic potential is applied to each of the permeable electrode bodies **12***a-d*, and fuel may be consumed from each or any of permeable electrode bodies **12***a-d*. As seen in step **380**, the method **330** may continue by determining if consumable fuel has been depleted from any permeable electrode body **12***a-d*. In an embodiment, a sensor, such as the sensing device **236** above, which may include a current or a voltage sensor, may be present in the cell **10**, and may indicate when consumable fuel has been depleted from one or more of the permeable electrode bodies **12***a-d*. If no depletion is detected, the discharging may continue as method **330** returns to step **370**. If, however, consumable fuel has been depleted from one or more of permeable electrode bodies **12***a-d*, then method **330** may continue to step **390**, wherein it may be determined whether there are any remaining permeable electrode bodies **12***a-d* that contain consumable fuel. This determination may be made simultaneously with the determination of depletion in step **380**, and may be made through a survey of sensing device(s) **236**, or by any other appropriate method.

If consumable fuel remains on one or more of permeable electrode bodies **12***a-d*, the method **330** may continue at step **400**, wherein the switching system **60** adjusts the plurality of switches so that any of permeable electrode bodies **12***a-d* that lack consumable fuel are disconnected from fuel electrode **12**. In an embodiment, consumption of fuel may initially be from the electrode body that is closest to the oxidant electrode **14** (such as, for example, permeable electrode body **12***d* in the illustrated embodiments above), and switching system **60** may disconnect permeable electrode body **12***d*, **12***c*, and **12***b* in that order, until all fuel is consumed from permeable electrode body **12***a*. Once none of the permeable electrode bodies **12***a-d* contain consumable fuel, or further discharging is no longer desired (or possible), the method may continue to step **410**, wherein the load L may be disconnected. In an embodiment, the load L may remain connected to the cell **10** when it is depleted, until the cell **10** is recharged, in which case it may be disconnected so that the cell **10** may be connected instead to the power supply PS. The method **330** may then end at **420**.

FIG. **16** depicts another embodiment of the cell **10**. As shown, the embodiment of cell **10** in FIG. **16** has the fuel electrode **12** with five electrode bodies **12***a-e*. Cell **10** further has a separate charging electrode **70** (i.e. a dedicated OEE), and an oxidant electrode **14**. As in the above embodiments, cell **10** includes a switching system **60** configured to selectively connect these electrodes and electrode bodies to one of the first terminal **130** or the second terminal **140**. The switching system **60** may include the controller **230**, configured to control the plurality of switches connected to it through circuitry **232**. As shown, the controller **230** may have the sensing device **236** included within it. Controller **230** may also receive instructions through the input **234** regarding how to control the switches.

As in the above embodiments, the cell **10** may have the bypass switch **150** configured to connect first terminal **130** directly to second terminal **140**, bypassing the cell **10** in cases such as where a fault is present within the cell **10**, or for any other reason where utilization of the cell **10** is not desired. The oxidant electrode **14** is again selectively connected to the second terminal **140** for discharging by oxidant electrode switch **160**, and the separate charging electrode **70** is again selectively connected to the second terminal **140** for charging by the charging electrode switch **170**. In the illustrated embodiment, the electrode bodies **12***b-e* may be selectively connected to either the first terminal **130** or the second terminal **140** by electrode body switches **425***b-e*, where “b” through “e” indicate which of electrode bodies **12***b-e* are associated with the respective switch. As is shown in the illustrated embodiment, electrode body switches **425***b-e* are configured to alternatively connect each of electrode bodies **12***b-e* to either a first bus **427***a* associated with electrode body **12***a* (and thus first terminal **130**), or a second bus **427***b* associated with the separate charging electrode **70** (and thus second terminal **140** through charging electrode switch **170**). In an embodiment, electrode body switches **425***b-e* may be characterized as Single Pole, Double Throw. In some embodiments, electrode body switches **425***b-e* may have three alternative settings, such that each electrode body **12***b-e* may be electrically connected to electrode body **12***a* (and first terminal **130**), separate charging electrode **70**, or disconnected from both electrode body **12***a* and separate charging electrode **70**. In an embodiment, such electrode body switches **425***b-e* may be characterized as Single Pole, Triple Throw.

During charging of the electrochemical cell **10**, power is applied from a power supply between first terminal **130** and second terminal **140**. Bypass switch **150** would be open so that there is no short between first terminal **130** and second terminal **140**. Since the cell **10** is in a charging mode, the oxidant electrode **14** is not utilized, so oxidant electrode switch **160** is also open. Accordingly, during charging the charging electrode switch **170** would be closed. As each of electrode bodies **12***b-e* may be selectively coupled to the anode or the cathode in this embodiment, charging techniques such as but not limited to the progressive OEE described above, or that disclosed in U.S. Provisional Patent Application No. 61/383,510 and U.S. patent application Ser. No. 13/230,549, each of which is incorporated herein in its entirety by reference, may be utilized. The operation of electrode body switches **425***b-e* in some embodiments is discussed in greater detail below.

Turning now to the flowchart in FIG. **17**, another aspect of the present invention may include an algorithm **430** associated with different charge modes for the electrochemical cell **10**. Although description of the operation of the algorithm **430** will be made with reference to the embodiment of the cell **10** in FIG. **16**, the algorithm **430** may be implemented onto any suitable embodiment of the electrochemical cell **10** by any appropriate mechanism. In one non-limiting embodiment, instead of utilizing the electrode body switches **425***b-e*, a more complex multiplexing switching system **60** may be utilized. In another non-limiting embodiment, a plurality of Single Pole, Single Throw switches may be configured in an array to allow for electrical connection or isolation between any two or more of electrode bodies **12***a-e* and separate charging electrode **70**. Any suitable system for electrically connecting electrode bodies **12***a-e* and/or separate charging electrode **70** may be utilized.

In an embodiment the algorithm **430** may include instructions, such as computer interpretable or readable instructions, that may program or otherwise control the controller **230**. In some embodiments, the algorithm **430** may be located on a system that is networked with or otherwise connected to controller **230**. In some embodiments, the algorithm **430** may be stored on a medium within controller **230**, or within any other controller that may allow programmatic control of the switches in switching system **60**.

As shown, algorithm **430** may be configured, at **440**, to select a particular charge mode for the cell **10**. The selection of the charge mode may be made by any appropriate determination criteria **450**. For example, in an embodiment the determination criteria **450** may include measurements **460** of the cell **10**. The measurements **460** of the cell **10** may be any appropriate measure of the status of the cell, including but not limited to sensor readings pertaining to the current status of fuel growth on permeable electrode bodies **12***a-e*, readings of the current electrical connections formed by the switching system **60**, measurements of a voltage and/or current from or through the cell **10**, or so on. To ascertain measurements **460**, controller **230** may utilize sensing device **236**, which in the current embodiment shows leads extending across the cell **10**, between first terminal **130** and second terminal **140**.

Measurements **460** may also include measures of the environment. In one embodiment, measurements **460** of the environment may include ascertaining the current time. For example, where the cell **10** is associated with a solar power system, charging earlier in the day may utilize a different charge mode than charging when the sun is closer to setting. Other measurements **460** of the environment are also possible. For example, in some non-limiting embodiments, measurements **460** may be of the environmental temperature, weather conditions, ambient light, movement of the cell **10** (i.e. if the cell **10** is utilized in a vehicle, different charge modes may be utilized for different speeds or braking styles), or so on.

Determination criteria **450** may also include manual overrides **470**, which may include any form of manual selection as to which charge mode is desired. Such a manual selection for manual overrides **470** may, in an embodiment, be provided to the controller **230** by input **234**. In an embodiment, determination criteria **450** may also include limits **480**, which for example may determine an appropriate charge mode based on exceeding predefined tolerances or settings. For example, limits **480** may be based on the measurements **460**, and include, for example, voltage difference between electrodes or electrode bodies, current impedance between electrodes or electrode bodies, or so on. In various embodiments, limits **480** may be based on voltage, current, slope of voltage, slope of current, charge capacity, or value of impedance or resistance, for example. Such limits **480** may be based on measurements **460** on or across one or more electrode bodies **12***a-e*, or on or across one or more cells **10**.

Once the charge mode is selected at **440**, the controller **230** may identify the charge mode at **490**, and proceed to charge the cell **10** accordingly. Although in an embodiment the charge mode may be one which utilizes a progressive OEE, such as that described above, in the illustrated embodiment the controller **230** is configured to select from two alternative charge modes, a progressive charge mode **500**, and a parallel charge mode **600**. In other embodiments, additional or alternative charge modes may be utilized, and may be in accordance with the algorithm **430**.

As shown in the illustrated embodiment, progressive charge mode **500** is a high capacity charge mode. This implies that the cell **10** is configured to be charged in a manner that provides a significant amount of density in the fuel growth between electrode bodies **12***a-e*. In some embodiments, this high capacity charge mode may take a longer interval of time to complete the charging process, but may enable the greatest amount of energy storage within the cell **10**. Such a charging mode may be useful for a number of applications, including but not limited to emergency backup power and uninterruptible power supplies, where a larger amount of power may be needed, and a relatively large amount of time is available to recharge the cell **10** following its use. In such applications the amount of energy stored in cells **10** is of greater importance than the charging rate. Because the charging process is roughly serial between the electrode bodies of the fuel electrode **12**, the charging rate is slower than in other embodiments. In the illustrated embodiment, wherein the cell **10** has five electrode bodies **12***a-e* in the fuel electrode **12**, and a separate charging electrode **70** (i.e. the dedicated oxygen evolving electrode, or OEE), the progressive charging mode **500** may include five phases.

When the cell **10** is uncharged, the progressive charge mode **500** may begin at a first phase **505**, wherein only the first electrode body **12***a* forms the cathode, while electrode bodies **12***b-e* and the separate charging electrode **70** form the charging electrodes. In the embodiment of FIG. **16**, the first phase **505** would have electrode body switches **425***b-e* connecting electrode bodies **12***b-e* to the separate charging electrode **70** through second bus **427***b*, which would be connected to second terminal **140** through charging electrode switch **170**. As such, only electrode body **12***a* would be electrically connected to first terminal **130**, creating a potential difference between electrode body **12***a* and the group of charging electrodes formed by the electrode bodies **12***b-e* and the separate charging electrode **70**. Fuel growth would then proceed on electrode body **12***a* towards the adjacent electrode body **12***b*.

Once the fuel growth reaches a sufficient amount that electrode body **12***a* and electrode body **12***b* short together at **510**, the progressive charge mode **500** would proceed to a second phase at **515**, wherein electrode bodies **12***a-b* form the cathode, while electrode bodies **12***c-e* and the separate charging electrode **70** form the charging electrodes. In the embodiment of FIG. **16**, the second phase **515** would have electrode body switch **425***b* disconnect electrode body **12***b* from the group of charging electrodes on second bus **427***b*, and electrically connect it to electrode body **12***a* through first bus **427***a*. The determination that electrode bodies **12***a-b* have shorted at **510** may be made through any suitable mechanism. For example, the sensing device **236** associated with controller **230** may measure a voltage drop or a current spike across the cell **10**. In other embodiments, other sensing devices **236** may ascertain the electrical connection, indicating the need to proceed to the second phase at **515**.

As fuel growth progresses through the cell **10**, the progressive charge mode **500** may electrically disconnect the contacting electrode body **12***b-e* from the second bus **427***b*, and connect it instead to the first bus **427***a*, progressively reassigning it form a charging electrode to a cathode. In embodiments wherein electrode body switches **425***b-e* are Single Pole, Triple Throw, the electrode body switches **425***b-e* may either be configured to connect contacting electrode bodies **12***b-e* along first bus **427***a*, or the electrode body switches **425** *b-e* may move to their electrically disconnected position, such that their electrical connection to first terminal **130** is through the fuel growth alone. As depicted in the flowchart of FIG. **17**, progressive charge mode **500** continues at **520** with determining the shorting of electrode bodies **12***b-c*, before proceeding to a third phase at **525**, where electrode body **12***c* would be disconnected from electrode body **12***d*, such as by the throwing of electrode body switch **425***c*. Fuel growth progresses until the shorting between electrode bodies **12***c-d* at **530**. At that time, a fourth phase would begin at **535**, with electrode body **12***d* being electrically disconnected from electrode body **12***e*, such as by the throwing of electrode body switch **425***d*, connecting electrode body **12***d* with the first bus **427***a*. At **540**, the fuel growth progression to electrically short electrode bodies **12***d* and **12***e* is determined, and a fifth phase **545** begins, where electrode body **12***e* is electrically disconnected from the separate charging electrode **70**, such as by the throwing of electrode body switch **425***e*, connecting electrode body **12***e* with the first bus **427***a*, such that none of the charging electrodes **12***b*-**3** are connected to the separate charging electrode **70** through the second bus **427***b*.

Once all electrode bodies **12***b-e* are connected with electrode body **12***a*, by the fuel growth through electrode bodies **12***a-e* and/or electrical connections through the first bus **427***a*, the fuel may continue to grow on electrode body **12***e* towards the separate charging electrode **70**, due to the potential difference between those electrodes. Eventually, at **550**, it may either be determined that electrode body **12***e* has shorted with the separate charging electrode **70**, indicating maximum fuel growth throughout the cell **10**, or a threshold charge capacity has been reached. Such a threshold capacity may be defined so that the cell does not "over-charge." For example, in some embodiments it may be undesirable that fuel growth reach and form an electrical connection to the separate charging electrode **70**. In an embodiment, the threshold charge capacity may be approximately 80-100% of the maximum possible charge capacity for the cell **10**. The measurement of capacity may be made by any suitable mechanism, including in some embodiments taking measurements with the sensing device **236**, or computing or estimating a charge capacity through controller **230**. Regardless, once the threshold capacity has been reached, or electrode body **12***e* has shorted with the separate charging electrode **70**, the cell may enter an idle state, to await a future discharge mode.

If during the selection of the charge mode at **440**, a desire for a faster charge is indicated, the parallel charge mode **600** may be selected at **490**. In the parallel charge mode **600**, mini-cells may be formed within the cell **10**, with alternating bodies between electrode body **12***a* and the separate charging electrode **70** acting as either an anode or a cathode. In an embodiment, the parallel charge mode **600** may be N times faster than progressive charge mode **500** (where N is the number of electrode bodies that metal fuel is being plated on). In an embodiment, the growth rate on a given electrode body is limited by the diffusion-limited current density of the metal fuel deposition, which is affected by a number of factors, including viscosity, concentration, diffusity, and so on. Although the parallel charge mode **600** would be faster than the progressive charge mode **500**, the fuel growth may be potentially less dense than in the progressive charge mode **500**, because the total charge deposited is limited by the time taken for electrical connections to form between all electrode bodies. In some embodiments, the energy density held by the cell **10** charged by the parallel charge mode **600** may be ¼ to ½ that of the cell **10** charged by the progressive charge mode **500**. Some examples of applications that would prefer the parallel charge mode **600** may include, for example, electric vehicles such as forklifts or cars, where a faster charge rate may be of greater importance than a larger charge density, like when the vehicle is being continuously used in close proximity to charging opportunities.

In an embodiment, the parallel charge mode **600** may begin at a first phase **605**, with electrode bodies **12***a*, **12***c*, and **12***e* connected to the first terminal **130**, while electrode bodies **12***b* and **12***d*, as well as the separate charging electrode **70**, are connected to the second terminal **140**. In the embodiment of FIG. **16**, to connect electrode bodies **12***c* and **12***e* to the first terminal **130**, such that electrode bodies **12***a*, **12***c*, and **12***e* are the initial cathodes during charging, electrode body switches **425***c* and **425***e* may initially be controlled to connect electrode bodies **12***c* and **12***e* to the first bus **427***a*. Likewise, for electrode bodies **12***b* and **12***d* to be initially coupled to the second terminal **140**, so that electrode bodies **12***b* and **12***d* (like separate charging electrode **70**) are anodes during charging, electrode body switches **425***b* and **425***d* may be controlled to connect electrode bodies **12***b* and **12***d* to the second bus **427***b*, where they are electrically connected to the second terminal **140** by charging electrode switch **170**, which is closed during charging.

As charging progresses during the first phase **605** of the parallel charge mode **600**, fuel growth may be bi-directional on the intermediate electrode bodies **12***c* and **12***e* that are acting as cathodes. In the embodiment of FIG. **16**, metal fuel is initially growing on electrode body **12***a* towards electrode body **12***b*, due to the potential difference therebetween. Fuel is also growing on electrode body **12***c* both towards electrode body **12***b* and towards electrode body **12***d* Likewise, bidirectional fuel growth is occurring on electrode body **12***e*, towards both electrode body **12***d* and the separate charging electrode **70**. During the charging, there may be, at **610**, a number of continuity tests. Specifically, for N electrode bodies, there may be N−1 continuity tests performed to determine if an electrical connection has formed between any of the anodes and any of the cathodes. For example, at **610***a*, it may be determined if electrode body **12***a* has shorted to electrode body **12***b* Likewise, at **610***b*, it may be determined if an intermediate electrode body (i.e. electrode body **12***c-d* in the illustrated embodiment) has shorted with either of the electrode bodies adjacent to it. Additionally, at **610***c*, it may be determined if the last electrode body (i.e. the "N−1"*th* electrode, which is electrode body **12***e* in FIG. **16**) has shorted with the separate charging electrode **70**.

If any of the continuity tests at **610** indicate an electrical connection has formed between an anode and a cathode, the parallel charge mode **600** may progress to an iterative next phase at **615**, wherein any shorted charging electrode (i.e. electrode body **12***b* or electrode body **12***d*) is electrically disconnected from the second terminal **140**. For example, if any short occurs between the first bus **427***a* and the second bus **427***b*, whichever of the switches **425***b-e* that can be thrown to eliminate that electrical connection may be thrown accordingly.

In an embodiment, any of the intermediate electrode bodies **12***b-e* may be reassigned from acting as anodes to acting as cathodes, or vice versa, based on the electrical connections formed during the parallel charge mode **600**. For example, if fuel growth electrically connects electrode body **12***c* (as a cathode) to electrode body **12***d* (as a charging electrode), while electrode body **12***e* is still growing fuel, the controller **230** may assign the pair of fuel-linked electrode bodies **12***c-d* to act together as a charging electrode, in that both electrode body switches **425***c-d* connect electrode bodies **12***c-d* to second terminal **140** via second bus **427***b*, so that bidirectional fuel growth of fuel on electrode body **12***e* continues. If fuel growth on electrode body **12***a* has electrically connected electrode bodies **12***a-b*, then electrode body **12***b* would be electrically disconnected from second bus **427***b*, such that a potential difference exists between electrode bodies **12***a-b* and electrode bodies **12***c-d*, so that additional fuel growth can occur on electrode bodies **12***a-b* (as a cathode) towards electrode bodies **12***c-d* (as a charging electrode).

If fuel growth on electrode body **12***e*, which is initially a cathode electrically connected to first terminal **130** via electrode body switch **425***e* and first bus **427***a*, causes a short with separate charging electrode **70**, controller **230** may then throw electrode body switch **425***e* to electrically disconnect electrode body **425***e* from first bus **427***a*, such that electrode body **12***e* and the separate charging electrode **70**, as well as the metal fuel therebetween, all act as an interconnected charging electrode. If electrode body **12***d* is then reassigned as a cathode (due to electrical connection with electrode body **12***c*, for example), then fuel growth may continue from electrode body **12***d* toward electrode body **12***e*, due to the potential difference therebetween.

In such a manner, the reassignment of electrode bodies **12***b-d* may progress, measured by the continuity tests at **610**, until, at **620**, either all electrode bodies **12***a-e* and the separate charging electrode **70** have shorted, or a threshold capacity for the cell **10** has been reached. Again, the reaching of the threshold capacity may be ascertained by any suitable mechanism, including in some embodiments taking measurements with the sensing device **236**, or computing or estimating a charge capacity through controller **230**. Regardless, once the threshold capacity has been reached, or all electrodes in the cell **10** have shorted, the cell may end the parallel charge mode **600** and enter an idle state, to await a future discharge mode.

In some embodiments, the controller **230** may be configured to charge the cell **10** such that some of the electrode bodies **12***a-e* are charging in accordance with progressive charge mode **500**, while others of electrode bodies **12***a-e* are charging in accordance with parallel charge mode **600**. In some embodiments, the varying desires of charge rate and energy density may be implemented in the charge mode selection at **440** throughout the charging of the cell **10**, such that the real time needs of the application utilizing the cell **10** may be taken into account. In an embodiment the controller **230** may measure typical discharge characteristics of the cell **10** over time, and modify the selection of the charge mode at **440** accordingly. As one non-limiting example, if the cell **10** is utilized in an electric vehicle that is utilized intermittently during daylight hours, but is not utilized at night, then the controller **230** may utilize the parallel charge mode **600** to quickly charge the vehicle as needed during the daylight, however may utilize the progressive charge mode at night, so that the greater amount of stored energy is held by the cell **10** for use the following day. In an embodiment, the controller **230** may be more sophisticated, and may compute a more complex optimal energy vs. charge rate, to provide the optimal quantity of run time based on the usage of the cell **10**.

It may be appreciated that in some embodiments the controller **230** may also be configured to discharge the cell **10** in a variety of modes. In some embodiments, the algorithm **430** may be further configured to select between a charging mode and a discharging mode. In other embodiments, a separate discharging algorithm may be provided for the discharge mode or modes. In some embodiments, differing modes of charging and discharging the cell **10** may be managed by a broader "cell operations" algorithm, which may be run on controller **230**, for example. In some embodiments, only the oxidant electrode **14** and a distal electrode body (i.e. permeable electrode body **12***a*) are electrically connected to the load L, such that only the fuel electrically connects the permeable electrode bodies **12***a-e*. During discharge, the fuel would progressively be consumed from electrode body **12***e* (proximal to the oxidant electrode **14**), towards the distal electrode body **12***a*. Once fuel is sufficiently consumed from each of the intermediate permeable electrode bodies **12***b-d*, those bodies would electrically disconnect from the fuel electrode **12** connected to the load L.

In some embodiments, the switching system **60** may be used to selectively connect the permeable electrode bodies **12***b-e* to the load L. In an embodiment, permeable electrode bodies **12***b-e* may all be connected to the load L throughout the discharging of the cell **10**. In other embodiments, control of which electrode bodies (i.e. permeable electrode bodies **12***b-e*) are electrically connected to the load L may be ascertained by the discharging algorithm, and may depend on a particular discharge mode. In an embodiment, the determination to selectively connect or disconnect the permeable electrode bodies **12***b-e* from the load L may be based on measurements, manual overrides, or limits, which may be similar to those of determination criteria **450** that are used to determine the charge mode at **440** described above. For example, the decision to connect or disconnect one of the permeable electrode bodies may be based on criteria such as the voltage, current, slope of voltage, slope of current, charge capacity, or value of impedance or resistance. Such measurements in various embodiments may be taken over one or more of the electrode bodies **12***a*-**12***e*, or across one or more cells **10**. In an embodiment, sensors such as sensing device **236** associated with one or more of the electrode bodies **12***a-e* and/or one or more of the cells **10** may be utilized to take the measurements.

As above, in an embodiment the sensing device **236** may be, for example, a voltmeter (digital or analog), potentiometer, or other voltage measuring device or devices, which can be used to determine when to modify the configuration of the plurality of switches. In some embodiments, the sensing device **236** may instead measure current, resistance, or any other electrical or physical property across or of the cell **10** that may be used to determine when to modify the configuration of the plurality of switches. In some embodiments, the controller **230** may control the switches of the switching system **60** based on the passage of increments of time. For example, in an embodiment the time for fuel consumption between adjacent electrode bodies may be known, and used to calculate when to operate the switching system **60** so as to disconnect depleted ones of the electrode bodies **12***b-e*.

The foregoing illustrated embodiments have been provided solely to illustrate the structural and functional principles of the present invention, and should not be regarded as limiting. To the contrary, the present invention is intended to encompass all modification, substitutions, and alterations within the spirit and scope of the following claims.

The subject matter claimed in the present application, owned by Fluidic, Inc., was developed as a result of activities undertaken within the scope of a license agreement qualifying as a joint research agreement under 35 U.S.C. §103(c)(2) and (3) between Fluidic, Inc. and Arizona Science and Technology Enterprises, LLC acting for the Board of Regents for and on behalf of Arizona State University, which was in effect prior to development of the claimed invention.

What is claimed is:

1. An electrochemical cell comprising:

a fuel electrode comprising a series of permeable electrode bodies arranged in spaced apart relation;

an oxidant electrode spaced apart from the fuel electrode;

a charging electrode selected from the group consisting of (a) the oxidant electrode, (b) a third electrode spaced from the fuel electrode and the oxidant electrode, and (c) a portion of the fuel electrode;

an ionically conductive medium contacting the electrodes;

a controller coupled to a plurality of the electrode bodies of the fuel electrode, said controller being configured to apply an electrical current between the charging electrode and at least one of the permeable electrode bodies with the charging electrode functioning as an anode and the at least one permeable electrode body functioning as a cathode, such that reducible metal fuel ions in the ionically conductive medium are reduced and electrodeposited as metal fuel in oxidizable form on the at least one permeable electrode body, so that said electrodeposition causes growth of the metal fuel among the permeable electrode bodies with the electrodeposited metal fuel establishing an electrical connection between the permeable electrode bodies,

wherein said controller is configured to selectively apply the electrical current to a different number of said permeable electrode bodies, each functioning as a cathode, based on at least one input parameter so as to adjust a rate and density of the growth of the electrodeposited metal fuel.

2. An electrochemical cell according to claim **1**, wherein said controller is configured to select between:

(1) a higher density progressive growth mode wherein the electrical current is applied to a terminal one of the permeable electrode bodies with the charging electrode functioning as the anode and the terminal electrode body functioning as the cathode such that the reducible metal fuel ions are reduced and electrodeposited as metal fuel

in oxidizable form on the terminal permeable electrode body, said electrodeposition causing growth of the metal fuel among the permeable electrode bodies such that the electrodeposited metal fuel establishes an electrical connection between the terminal electrode body and each subsequent permeable electrode body with said reduction and deposition occurring on each subsequent permeable electrode body upon establishment of said electrical connection; and

(2) a higher rate growth mode wherein the electrical current is applied simultaneously to a plurality of said electrode bodies with the charging electrode functioning as the anode and each of the plurality of electrode bodies functioning as cathodes such that the reducible metal fuel ions are reduced and electrodeposited as metal fuel in oxidizable form on the terminal permeable electrode body, said electrodeposition causing growth of the metal fuel among the permeable electrode bodies.

3. An electrochemical cell according to claim **2**, wherein the controller is configured to apply the electrical current in the higher rate growth mode simultaneously to all the electrode bodies.

4. An electrochemical cell according to claim **2**, wherein the controller is configured to apply the electrical current in the higher rate growth mode simultaneously to less than all the electrode bodies.

5. An electrochemical cell according to claim **1**, wherein said controller is configured to vary the number of electrode bodies to which the electrical current is applied while performing a recharging operation.

6. An electrochemical cell according to claim **1**, wherein the controller is coupled to a sensor that senses a condition of the electrochemical cell, and wherein the input parameter is input by the sensor.

7. An electrochemical cell according to claim **1**, wherein the input parameter is input via a user input.

8. An electrochemical cell according to claim **1**, wherein the input parameter is a limit parameter and wherein the controller is further configured to compare a cell property to the limit parameter.

9. An electrochemical cell according to claim **8**, wherein the cell property is a voltage, a capacity, an impedance between electrodes, a slope of electrode voltages, a current, a resistance to a sensing electrode, or a shorting to the charging electrode.

10. An electrochemical cell according to claim **1**, wherein the ionically conductive medium is an electrolyte.

11. An electrochemical cell according to claim **1**, further comprising a plurality of switches operatively coupled between the controller and the plurality of electrode bodies, wherein the controller is configured to control an open state and a closed state for each of the plurality of switches, to selectively apply the electrical current to some of the plurality of electrode bodies.

12. An electrochemical cell according to claim **2**, wherein in the higher rate growth mode, the electrical current is applied simultaneously to the plurality of electrode bodies such that the charging electrode comprises some of the plurality of electrode bodies functioning as anodes and the fuel electrode comprises some of the plurality of electrode bodies functioning as cathodes, and wherein each of the plurality of electrode bodies functioning as cathodes are separated from one another by the plurality of electrode bodies functioning as anodes.

13. An electrochemical cell according to claim **1**, wherein the controller is a charge/discharge controller.

14. An electrochemical cell according to claim **2**, wherein the controller is a charge/discharge controller.

15. An electrochemical cell according to claim **6**, wherein the controller is a charge/discharge controller.

16. An electrochemical cell according to claim **8**, wherein the controller is a charge/discharge controller.

17. An electrochemical cell according to claim **12**, wherein the controller is a charge/discharge controller.

18. A method of recharging an electrochemical cell, wherein the electrochemical cell comprises:

a fuel electrode comprising a series of permeable electrode bodies arranged in spaced apart relation;

an oxidant electrode spaced apart from the fuel electrode;

a charging electrode selected from the group consisting of (a) the oxidant electrode, (b) a third electrode spaced from the fuel electrode and the oxidant electrode, and (c) a portion of the fuel electrode;

an ionically conductive medium contacting the electrodes;

a controller coupled to a plurality of the electrode bodies of the fuel electrode, said controller being configured to apply an electrical current between the charging electrode and at least one of the permeable electrode bodies with the charging electrode functioning as an anode and the at least one permeable electrode body functioning as a cathode, such that reducible metal fuel ions in the ionically conductive medium are reduced and electrodeposited as metal fuel in oxidizable form on the at least one permeable electrode body, so that said electrodeposition causes growth of the metal fuel among the permeable electrode bodies with the electrodeposited metal fuel establishing an electrical connection between the permeable electrode bodies,

wherein said controller is configured to selectively apply the electrical current to a different number of said permeable electrode bodies based on at least one input parameter so as to adjust a rate and density of the growth of the electrodeposited metal fuel;

the method being performed using said electrochemical cell and comprising:

selecting, based on the at least one input parameter, between a higher density progressive growth mode and a higher rate growth mode;

charging the electrochemical cell based on the selected one of the higher density progressive charge mode and the higher rate growth mode;

wherein, in the higher density progressive growth mode, said charging comprises:

applying the electrical current to a terminal one of the permeable electrode bodies, with the charging electrode functioning as the anode and the terminal electrode body functioning as the cathode, such that the reducible metal fuel ions are reduced and electrodeposited as metal fuel in oxidizable form on the terminal permeable electrode body, said electrodeposition causing growth of the metal fuel among the permeable electrode bodies such that the electrodeposited metal fuel establishes an electrical connection between the terminal electrode body and each subsequent permeable electrode body with said reduction and deposition occurring on each subsequent permeable electrode body upon establishment of said electrical connection; and

wherein, in the higher rate growth mode, said charging comprises:

applying the electrical current simultaneously to a plurality of said electrode bodies, with the charging electrode functioning as the anode and each of the plurality of electrode bodies functioning as cathodes, such that the reducible metal fuel ions are reduced and electrodeposited as metal fuel in oxidizable form on the terminal permeable electrode body, said electrodeposition causing growth of the metal fuel among the permeable electrode bodies; and

disconnecting the electrical current to discontinue the charging.

19. A method of recharging the electrochemical cell according to claim **18**, wherein, in the higher rate growth mode, the charging electrode comprises one or more of the plurality of electrode bodies adjacent to the plurality of the electrode bodies functioning as cathodes.

20. A method of recharging the electrochemical cell according to claim **18**, wherein, in the higher rate growth mode, said charging further comprises performing continuity testing on one or more of the plurality of electrode bodies to determine electrical connections formed between any of the electrode bodies functioning as cathodes and any of the charging electrode; and disconnecting any of the electrode bodies.

21. A method of recharging the electrochemical cell according to claim **18**, wherein the at least one input parameter comprises measurements obtained by a sensor associated with the electrochemical cell, and wherein the method further comprises sensing, with the sensor, the measurements of the electrochemical cell.

22. A method of recharging the electrochemical cell according to claim **18**, wherein the at least one input parameter comprises a user selection of the higher density progressive charge mode or the higher rate growth mode, input via a user input, wherein the method further comprises receiving a user selection via the user input.

23. A method of recharging the electrochemical cell according to claim **18**, wherein the at least one input parameter is a limit parameter and wherein the controller is further configured to compare a cell property to the limit parameter to perform said selecting.

24. A method of recharging the electrochemical cell according to claim **18**, wherein, in the higher rate growth mode, said charging comprises applying the electrical current simultaneously to all of the electrode bodies.

25. A method of recharging the electrochemical cell according to claim **18**, wherein, in the higher rate growth mode, said charging comprises applying the electrical current simultaneously to less than all of the electrode bodies.

26. A method of recharging the electrochemical cell according to claim **18**, wherein said charging comprises varying, with the controller, the number of electrode bodies to which the electrical current is applied while performing a recharging operation.

27. A method of recharging the electrochemical cell according to claim **18**, wherein the ionically conductive medium of the electrochemical cell is an electrolyte.

28. A method of recharging the electrochemical cell according to claim **18**, wherein the electrochemical cell further comprises a plurality of switches operatively coupled between the controller and the plurality of electrode bodies, and wherein said charging comprises controlling an open state and a closed state for each of the plurality of switches with the controller, to selectively apply the electrical current to some of the plurality of electrode bodies.

29. A method of recharging the electrochemical cell according to claim **18**, wherein in the higher rate growth mode, said charging comprises applying the electrical current simultaneously to the plurality of electrode bodies such that the charging electrode comprises some of the plurality of electrode bodies functioning as anodes and the fuel electrode comprises some of the plurality of electrode bodies functioning as cathodes, and wherein each of the plurality of electrode bodies functioning as cathodes are separated from one another by the plurality of electrode bodies functioning as anodes.

30. A method according to claim **18**, wherein the controller is a charge/discharge controller.

31. A method according to claim **21**, wherein the controller is a charge/discharge controller.

32. A method according to claim **23**, wherein the controller is a charge/discharge controller.

33. A method according to claim **28**, wherein the controller is a charge/discharge controller.

* * * * *